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ASD TECHNICAL REPORT 61-85

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LUBRICATION RESEARCH AND TEST METHOD DEVELOPMENT FOR AEROSPACE PROPULSION SYSTEMS

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L. W. LEW
H. E. STAPH

SOUTHWEST RESEARCH INSTITUTE

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AERONAUTICAL SYSTEMS DIVISION

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MAY 1961

MATERIALS CENTRAL
CONTRACT NO. AF 33(616)-7223
PROJECT NO. 3044

AERONAUTICAL SYSTEMS DIVISION
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report was prepared at Southwest Research Institute under USAF Contract No. AF 33(616)-7223. The contract was initiated under Project No. 3044, "Aviation Lubricants," Task No. 30169, "Turbojet Engine Lubricants," and Task No. 30340, "Missile and Space Vehicle Propulsion Lubricants." The work was administered under the direction of Materials Central, Aeronautical Systems Division, with Messrs. G. A. Beane, K. L. Berkey and R. C. Sheard acting as project engineers.

This report covers work performed in the period of March 15, 1960, through January 14, 1961.

ABSTRACT

The work performed under this program was concerned with lubrication problems associated with advanced primary and secondary propulsion systems for aviation and space applications. The program was divided into four principal phases of investigation: gear lubrication, bearing lubrication, lubricant oxidation, and impact sensitivity of materials in contact with strong oxidizers. The effort has been devoted largely to gear and bearing lubrication. In the gear lubrication and the bearing lubrication phases, the emphasis has been primarily on the development of suitable test methods for determining the capabilities of liquid lubricants intended for use in high-temperature applications. Lubricant oxidation determinations have been made on organic liquid lubricants using the equipment and test procedure recommended by the Celanese Chemical Company. The impact sensitivity work has been concerned with the impact sensitivity of liquid lubricants, greases and sealants in contact with liquid oxygen and with test method development in an endeavor to improve the repeatability and reproducibility of the impact test using the ABMA impact tester.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Marc P. Dunnam

Marc P. Dunnam
Chief, Fuels and Lubrication Branch
Applications Laboratory
Materials Central

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I. INTRODUCTION

A. Objectives and Scope

This report summarizes the work performed at Southwest Research Institute during the period of March 15, 1960, through January 14, 1961, on a program of lubrication research and test method development for aerospace propulsion systems, under USAF Contract No. 33(616)-7223.

For nearly seven years, extending from April 1, 1953, through January 14, 1960, SwRI was engaged in a continuing USAF program of lubrication research and lubricant test method development with special reference to aviation gas turbine lubricant applications. This work was conducted under USAF Contracts AF 33(616)-498, AF 33(616)-2659, AF 33(616)-3820, and AF 33(616)-6232, and has been described in considerable detail in numerous reports included in the Bibliography of this report. A sufficiently adequate account of the work appears in four summary reports (0. 82, 0. 83, 0. 84, 0. 85)* issued under the respective contracts.

The present program has been a continuation of certain areas of investigation initiated under the previous contracts. The specific areas of investigations are as follows:

(1) Lubricants and lubrication

 (a) Gear lubrication

 (b) Bearing lubrication

 (c) Lubricant oxidation

(2) Impact sensitivity of materials in contact with strong oxidizers.

A brief resumé of the major accomplishments made during this contract period appears in the section which follows. More detailed accounts of the work are presented in the succeeding chapters.

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*Superscript numbers in parenthesis refer to the Bibliography.

Manuscript released by authors January 1961 for publication as an ASD Technical Report.

B. Highlights of Accomplishments

During this contract period, the emphasis in the lubricants and lubrication area has continued to be primarily on determining the capabilities of organic liquid lubricants operating at high temperatures for extended periods of time. In addition, considerable attention has been given to problems associated with missile and space vehicles.

In the gear lubrication phase, the WADD high-temperature gear machine[0.85] has been used in a continued investigation of the high-temperature load-carrying capacity of ten selected organic liquid lubricants using two different designs of Nitralloy N steel test gears. An increase in the load-carrying capacity was noted for all lubricants when either of the two designs of Nitralloy N steel gears were used. The increases noted were not as large as those noted earlier[0.85] when M-50 steel gears were tested. However, significant increases are evident at both 165 and 400°F test temperatures when compared to results obtained using the standard Ryder test gears (AMS-6260 steel). The development of a suitable test method for determining the effect of lubricants on gear tooth fatigue at 400°F was initiated. In addition, significant progress has been made in the development of high-temperature research techniques involving induction heating of the test gears, measurement and control of test gear blank temperature by means of infrared radiation, and inspection of the test gears by means of closed-circuit television.

Bearing lubrication research has been conducted along two parallel lines, one employing relatively large (85-mm bore) angular-contact ball bearings operating at moderate speeds but heavy loads, and the other employing relatively small (20-mm bore) angular-contact ball bearings operating at light loads but very high speeds. The 85-mm thrust bearing program has been devoted principally to the development of a test method for determining the effect of lubricants on bearing fatigue. Two test methods were investigated, one employing a constant-load procedure and the other employing a step-load procedure. The step-load procedure was investigated in an effort to reduce the normally long test periods encountered using the constant-load procedure. Seven bearing fatigue failures were obtained on one MIL-L-9236B lubricant using the constant-load procedure in periods varying from 159 to 564 hr of operation. Ten bearing fatigue failures were obtained on the same MIL-L-9236B lubricant using the step-load procedure in periods varying from 50.5 to 360 actual test hours. However, no correlation of the results obtained using the two different test procedures has been possible; therefore, additional development work on the test procedures has been recommended.

The 20-mm thrust bearing program has been concerned with an investigation of the performance and deterioration characteristics of lubricants in the

temperature range of 500 to 700°F. Due to a large number of bearing and rig failures, no clear-cut indication of the performance capability of the five lubricants tested was obtained. Modifications were made to the 20-mm bearing machine in an effort to alleviate the conditions causing the bearing and rig failures. Preliminary runs on the modified 20-mm bearing machine have indicated areas where improvements are still desirable. It appears that bearing seizure due to the loss of internal clearances has been eliminated; however, temperature control with the modified machine has not been altogether satisfactory.

The construction of a lubricant oxidation test apparatus in accordance with Celanese Chemical Company specifications was completed. Oxidation tests were conducted on nine different lubricants using the Celanese oxidation test procedure. From the relatively small amount of data and experience obtained to date, it appears that a reasonable degree of repeatability and reproducibility may be possible with this test apparatus and procedure.

In the impact sensitivity phase of the program, data were obtained on 22 sample fluids and one grease sample submitted by WADD. Six of these sample fluids were tested for the Pre-Cooperative Test Program No. 2 and the Cooperative Test Program No. 2. Data were obtained on the effect of sample thickness on impact sensitivity. It was found that sample thicknesses below 0.040 in. appreciably affected the sensitivity of fluid samples, and, that with a constant volume of different test samples, the thickness of the sample varied depending upon certain physical properties of the test sample. Threshold value repeatability data were obtained on three different fluid samples using the ABMA impact tester which showed a reasonable repeatability level for the apparatus and procedure. In addition, a complete set of drawings for a proposed standard impact tester were submitted to WADD for approval along with a proposed standard test procedure.

C. Test Fluids

A number of fluids have been used in the current program. Most of the fluids are of proprietary makes. Such characteristics of the fluids as can be enumerated without violating the proprietary interests involved are presented in Table 45 of Appendix I.

II. GEAR LUBRICATION

A. General Remarks

The objectives of the gear lubrication phase were to develop apparatus and techniques for evaluating lubricants as to their load-carrying capacity and fatigue characteristics at high temperatures, speeds, and loads; and to evaluate advanced lubricant formulations for use in advanced gas turbine engines with respect to these factors.

During the contract period, investigations of the load-carrying capacity of selected lubricants at 400°F were made using Nitralloy N steel test gears of two different designs. In addition, comparative tests were run at 165°F using Nitralloy N steel test gears and standard Ryder test gears, in an effort to determine any possible correlation that may exist between results obtained under different test conditions. It was found that no organized correlation existed between the results obtained with one gear material under a given set of operating conditions and those obtained with another gear material under a different set of operating conditions. Gear blank temperature measurements were made with an infrared radiometer during approximately 160 tests. In general, it was found that the gear blank temperature increased with an increase in scuff level

Load-carrying capacity tests with the gear blank temperature controlled at 400°F were initiated. Gear blank temperature control was obtained by means of an infrared radiometer in conjunction with a strip chart recorder-controller. Nitralloy N steel test gears of SwRI design were used. It was found that the scuff-limited load results obtained with gear blank temperature maintained at 400°F were higher than the results obtained using the standard 400°F test procedure.

Investigations of gear fatigue characteristics of selected lubricants at 400°F under various conditions of speed and load, using SwRI design Nitralloy N steel test gears, were initiated. The data obtained to date are limited. However, the use of tip-relieved test gears in conjunction with a low tooth load to give a low level of scuff appeared to show promise for further investigations.

The visual microscopic method of test gear inspection has been replaced by a closed-circuit television system. The scuff ratings obtained by the television method were found to be well within the normal accuracy of visual-microscopic ratings.

The manually controlled load system on both WADD high-temperature gear rigs has been replaced with an automatic recorder-controller load system. The use of this system has afforded automatic setting and control of the load oil pressure to within ± 0.25 psi over a range of 0 to 120 psig. Satisfactory operation has been obtained with this system in both the load-carrying capacity and gear fatigue programs.

Hardness determinations were made on both new and used test gears of different materials and designs. It was found that the case hardness of the high-temperature test gears remained unchanged after a 400°F load-carrying capacity test. On the other hand, the standard Ryder test gears suffered a significant loss in case hardness after a load-carrying capacity test especially at 400°F.

Case thickness measurements were made on a few SwRI design Nitralloy N steel test gears used in the fatigue studies. No appreciable deviations from case thickness specifications were noted in the gears examined.

B. Development of Test Equipment and Techniques

1. WADD High-Temperature Gear Machine

All of the experiments reported herein were conducted using two WADD high-temperature gear machines developed earlier.(0.85) A cross section of this machine is shown in Figure 1. Its operating principle is identical to that of the standard Ryder gear machine.(10.01) However, improvements in material and design permit its operation at speeds up to 30,000 rpm, and test gear temperatures of 800°F or higher. As shown in Figure 1, the WADD high-temperature gear machine differs from the standard Ryder gear machine in that each shaft is supported by two double-row roller bearings instead of three journal bearings as used on the standard machine. Screw-thread type nonrubbing seals, rather than elastomer seals, are used to separate the test oil and support oil chambers. The case is made of tool steel to improve structural stability at elevated temperatures. The high-temperature gear machine with high-temperature test gears and the induction heating coil installed is shown in Figure 2. The induction heating coil is normally rigidly attached to the end cover, and is removed with the cover each time the cover is removed.

In the operation of the gear machine, the test gear tooth load is obtained by the application of an axial hydraulic load on the end of the driven shaft. This hydraulic load is converted into a tangential load on the test gears through the action of the helical slave gears. The test gear tooth load is computed from the hydraulic load and the geometry of the load system.

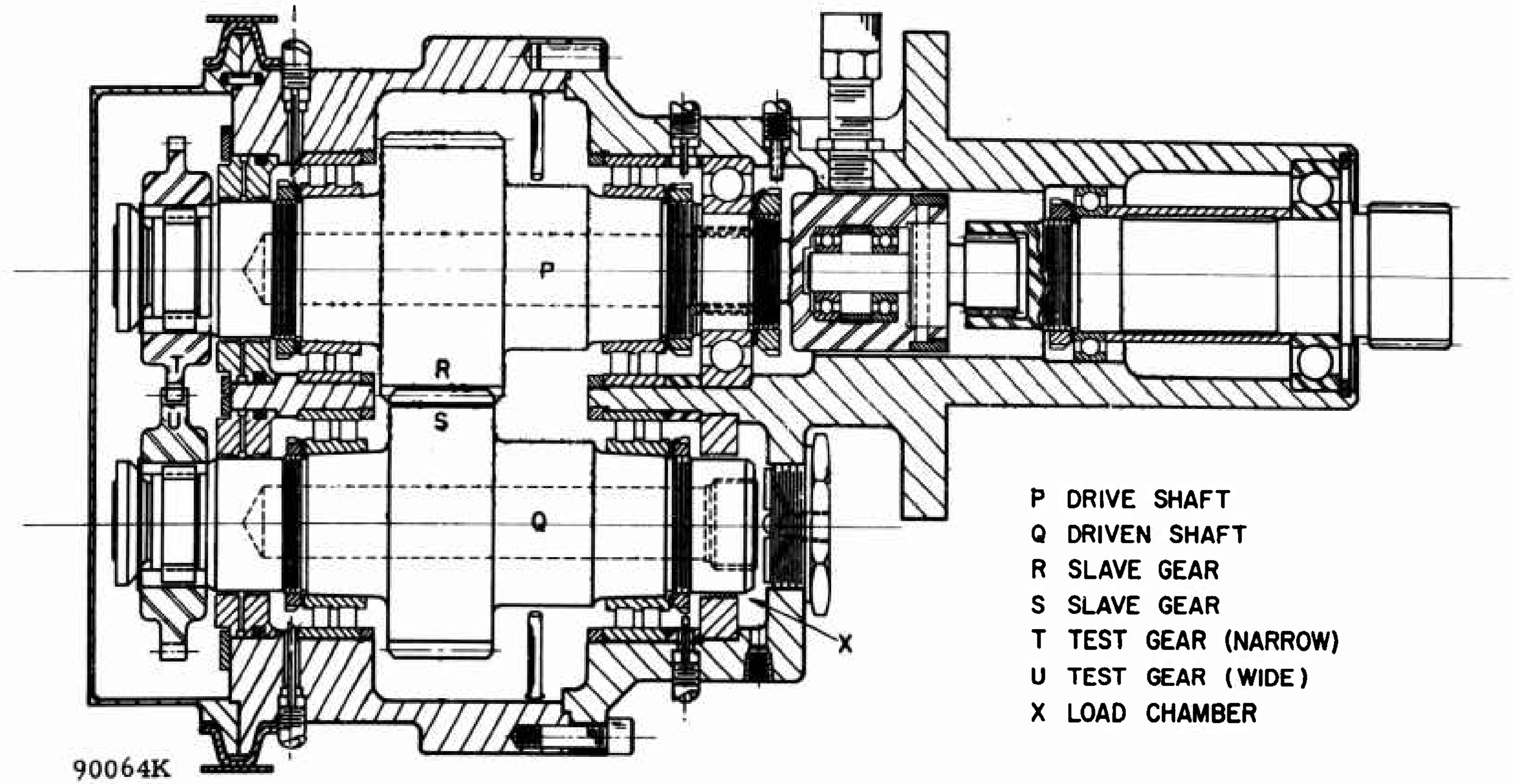


FIGURE 1. CROSS SECTION OF WADD HIGH-TEMPERATURE GEAR MACHINE

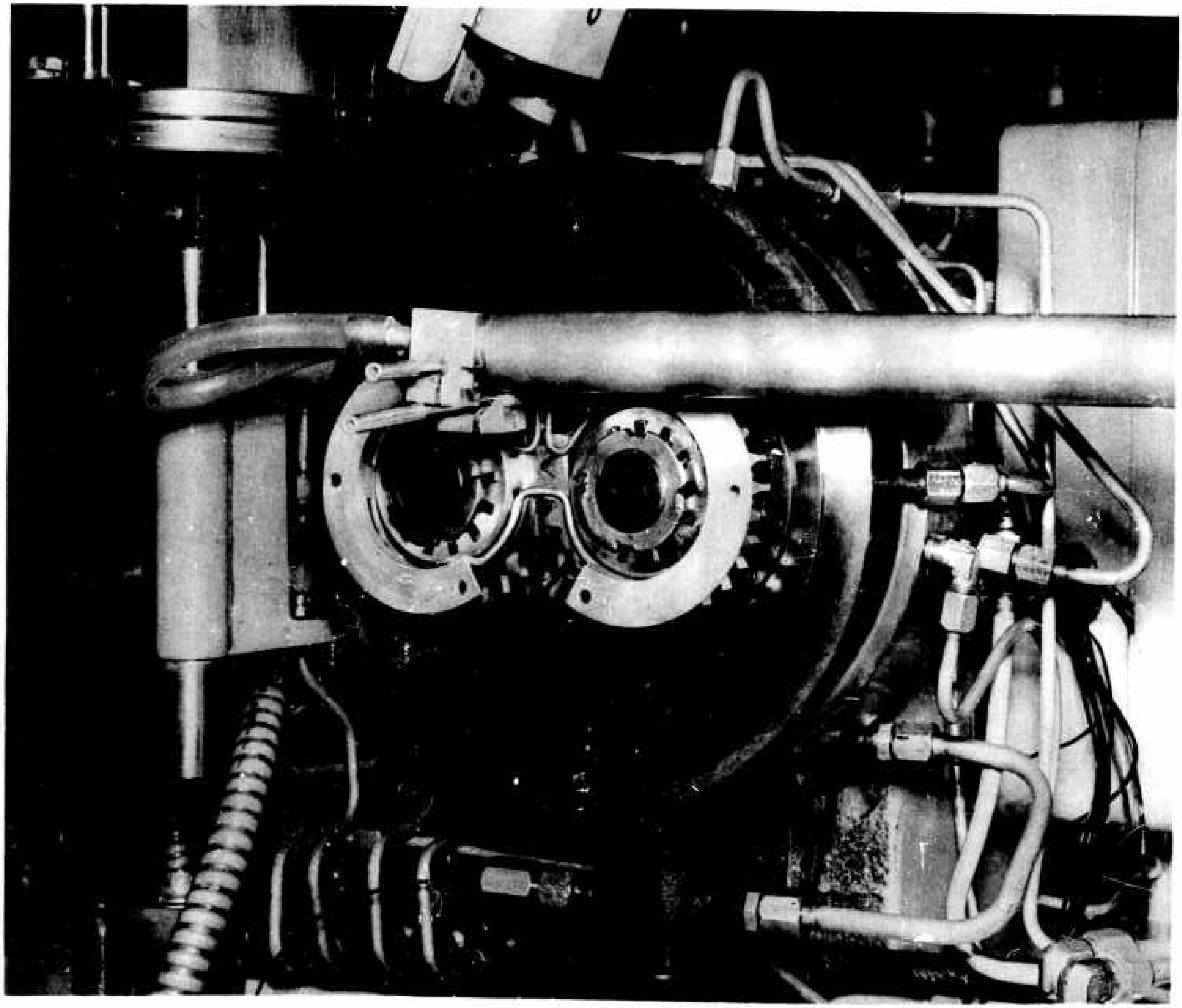


FIGURE 2. PHOTOGRAPH OF WADD HIGH-TEMPERATURE GEAR MACHINE WITH HIGH-TEMPERATURE TEST GEARS AND INDUCTION HEATING COIL INSTALLED

The high-temperature gear machines are driven by modified standard Erdco drive units with the standard 50-hp drive motor. The standard drive units were modified during the previous contract period(0.85) to permit operation at speeds of 30,000 rpm by changing the step-up gear ratio from 4.53:1 to 9.25:1.

When the machines were first operated at 400°F, bearing failures were encountered with both the roller bearings and the ball bearings. The roller bearing failures were generally caused by lack of lubrication due to plugged oil jets or partially plugged jets. This condition was magnified by the lack of suitable lubricants that could be satisfactorily used as support oil at the 400°F temperature level. In order to significantly reduce the number of bearing failures due to jet plugging, it was necessary to clean all oil jets in the machines every 6 hours, or after each single determination. To facilitate easier and less time-consuming cleaning operations, the jets to the roller bearings were modified such that they could be removed for cleaning. The ball bearings failed due to a decrease in the internal clearance. Therefore, it was necessary to employ ball bearings (SKF 6208-C3) having larger internal clearances than the standard bearings. In addition, the thrust bearing (on the rear of the drive shaft) was later changed to an M-50 steel bearing (Fafnir AAMM208-2-SMBR). To minimize bearing failures on the jack shaft, the oil-in temperature to these bearings was reduced to 165°F by employing a dual-temperature support oil system described in detail in a later section of this report. These changes made it possible to obtain a reliability level with the high-temperature gear machine comparable to that of the standard Ryder gear machine operating under less severe temperature conditions. The bearing life has been increased from approximately 100 hours to 450 hours for the roller bearings, and the M-50 thrust bearing is still functioning satisfactorily after 2000 hours of operation.

The WADD high-temperature gear rigs have operated satisfactorily for approximately 2800 hours, during scuff-limited load and fatigue testing, over a range of temperatures up to 400°F and speeds of 10,000 rpm. The machines have also performed satisfactorily for short periods at speeds up to 30,000 rpm and at test gear blank temperatures up to 700°F.

2. 400°F Test Oil System and Dual-Temperature Support Oil System

For the 400°F gear tests, where some degree of test oil deterioration during test appears to be unavoidable and must therefore be minimized or controlled as much as possible, it was felt that direct contact of the test oil with a high-wattage immersion heater should be avoided. With this in mind, a 400°F test oil system having a 2-gallon capacity was designed and two complete assemblies were fabricated during the previous contract period.(0.85)

In developing the support oil system for the 400°F gear program(0.85), attempts were first directed toward modifying the standard Erdco support oil system. However, it was soon found that for satisfactory sustained 400°F operation, very extensive modifications were required. The result was the evolution of a new support oil system. This system represented a compromise between an experimental requirement and a maintenance requirement. The experimental requirement was that portions of the gear machine adjacent to the test gears must be maintained at the temperature of the test oil in order to minimize the heat loss from the test gears under equilibrium operating conditions. The maintenance requirement was that other parts of the gear rig should operate at a lower temperature in order to maintain the normal reliability of these parts.

400° Test Oil System. A schematic diagram and photograph of the 400°F test oil system are shown in Figures 3 and 4 respectively. It will be noted that the test oil is heated by means of a heat exchanger placed inside an insulated test oil sump. By using this means of heating, the test oil is subjected only to the controlled temperature of the heating fluid being circulated through the heating coils. The flow of the heating fluid through the heat exchanger is controlled by a thermocouple located in the test oil sump through the action of an on-off controller. The test oil is circulated around the coils of the heat exhanger by the action of the over capacity test oil pump, which supplies enough by-passed oil to provide sufficient circulation. It will also be noted that all of the necessary supporting items, such as the filter, pressure pump, by-pass valve, have been placed inside the 400°F sump, thereby eliminating considerable heat loss to the ambient. No test oil scavenge pump is required as long as the test oil flow remains below 1500 ml/min.

Dual-Temperature Support Oil System. A schematic diagram of the dual-temperature support oil system is presented in Figure 5. Note that the system has a section which operates at a low temperature (about 165°F). This section supplies the lubrication required for the Boston gear box and the bearings in the adapter block, thereby maintaining the normal life of the bearings located in these areas. All of the areas lubricated by the low-temperature section are remotely located from the test gear section. The 400°F section provides load oil and lubrication for all points forward of the jack shaft in the high-temperature gear machine. This high-temperature section is an improvement over that developed during the previous contractual period.(0.85) Considerable difficulty was experienced with the previous system because of loss of support oil and heating fluid due to seal leakage in the support oil pressure pump, support oil scavenge pump, and the test oil and support oil heating fluid pumps. While leakages of this type do not

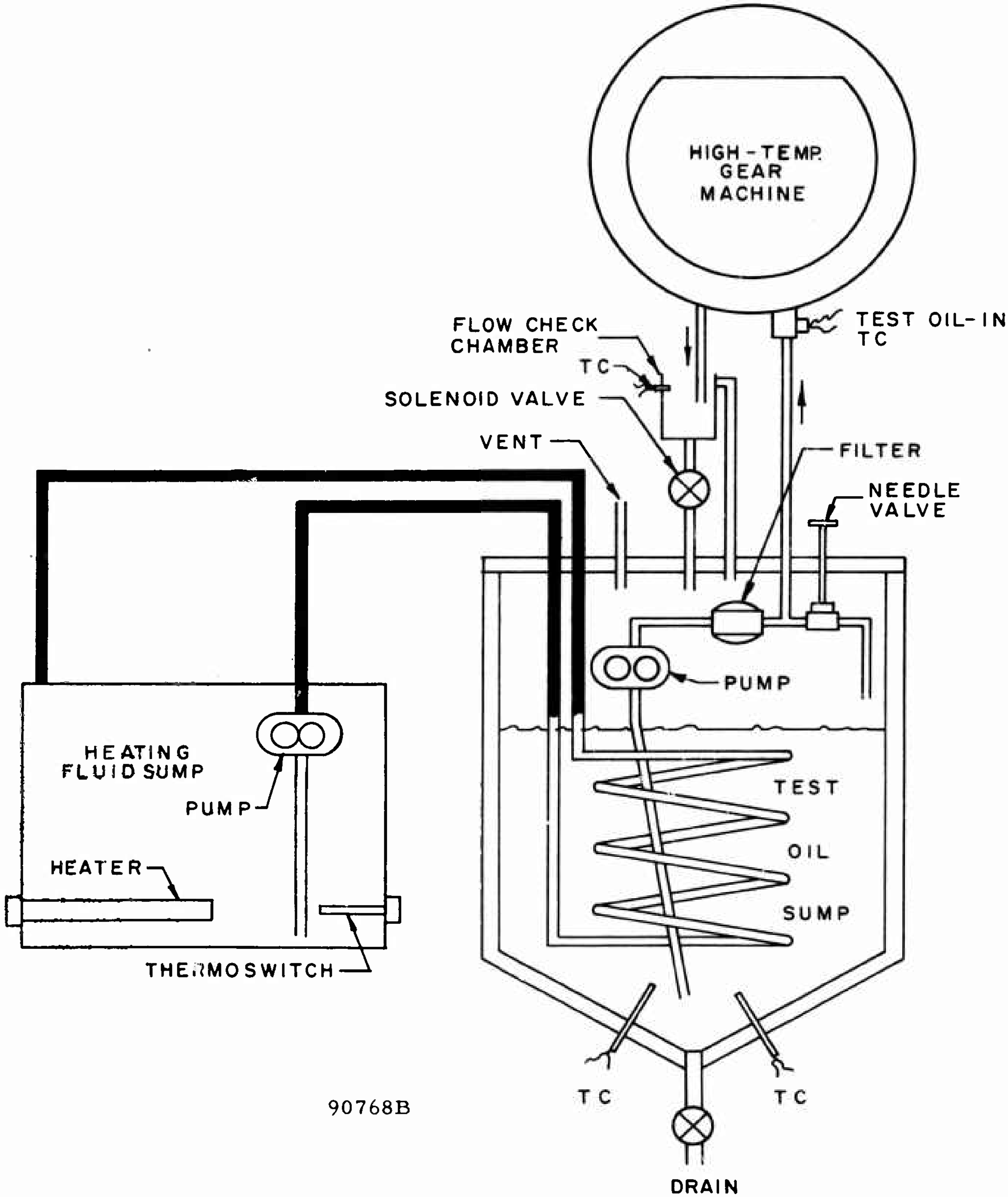


FIGURE 3. SCHEMATIC DIAGRAM OF 400° F TEST OIL SYSTEM

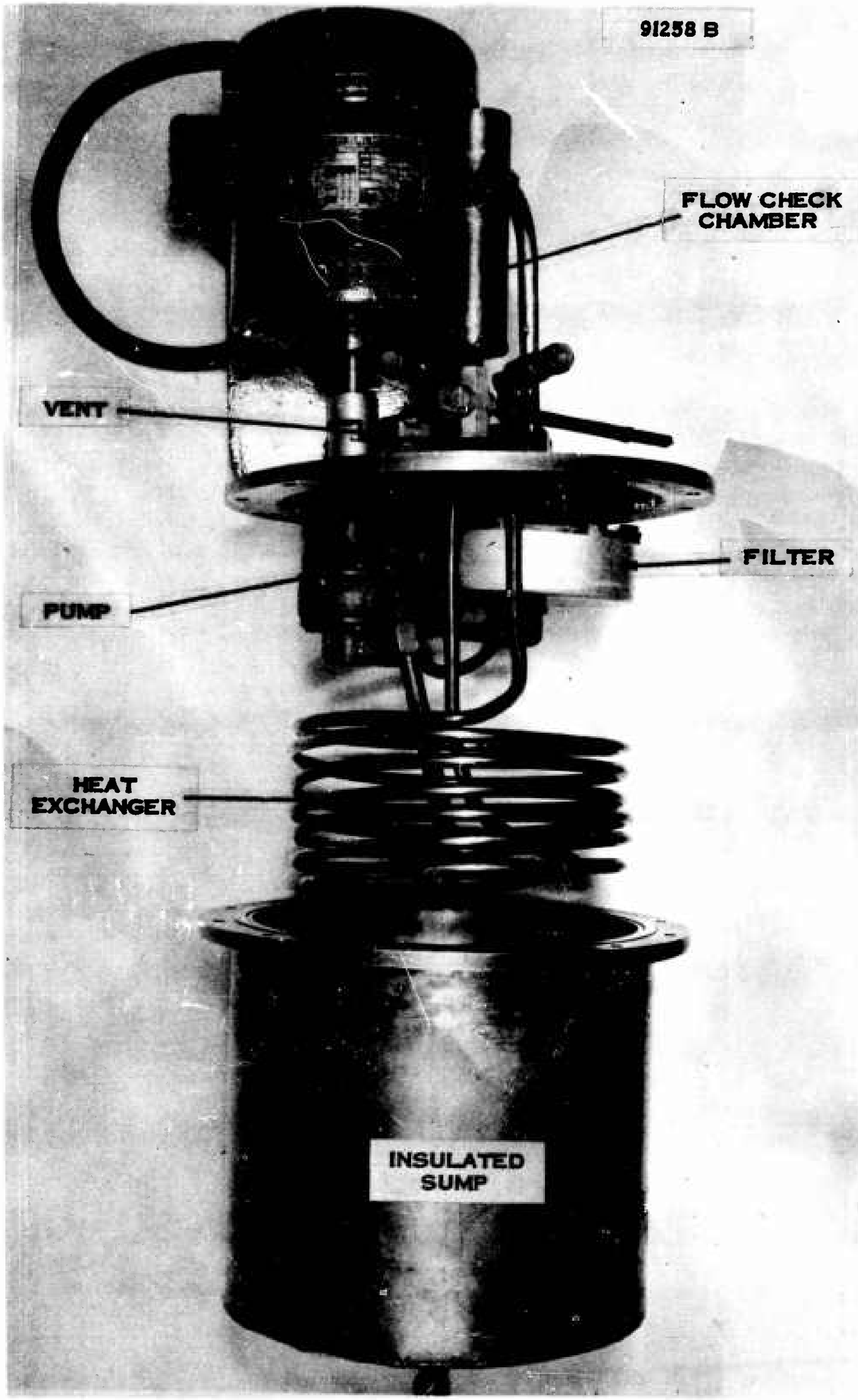


FIGURE 4. EXPLODED PHOTOGRAPHIC VIEW OF 400°F TEST OIL SYSTEM

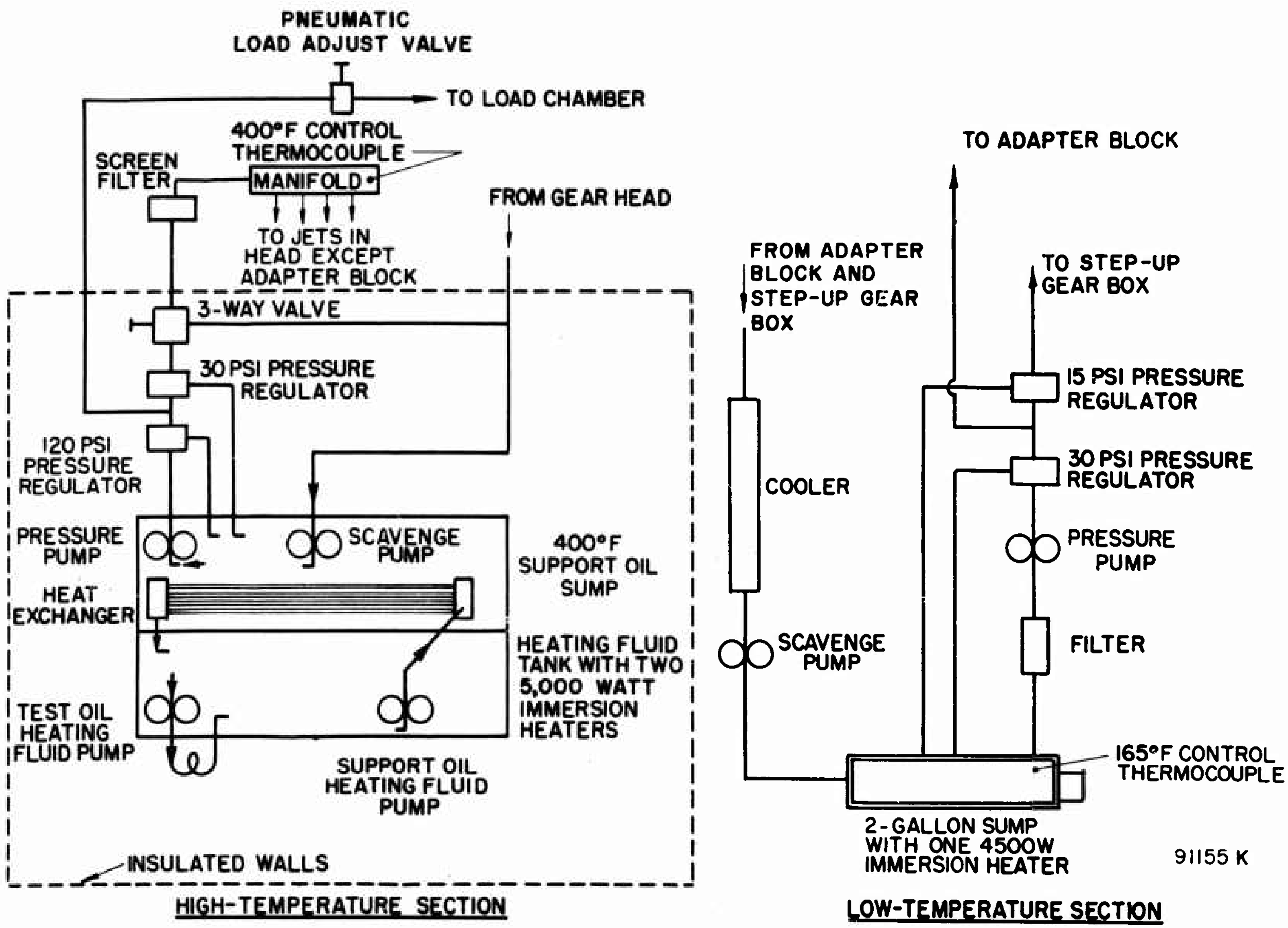


FIGURE 5. SCHEMATIC DIAGRAM OF DUAL-TEMPERATURE SUPPORT OIL SYSTEM

in any way influence the test results, they nevertheless increase the respective oil consumption, constitute a cleaning problem for the test rig, and increase the down time during routine maintenance periods. Based upon the satisfactory operation of the test oil system after placing the test oil pump in the test oil sump, it was decided to locate both the support oil pressure pump and support oil scavenge pumps inside the support oil sump, and the test oil heating fluid pump and the support oil heating fluid pump inside the heating fluid sump which adjoins the support oil sump. A photograph of this system is shown in Figure 6 The performance of this system has been satisfactory. However, some difficulty has been experienced with support oil failures. The maximum life of the support oil (a MIL-L-7808 type oil) has been found to be approximately 80 hours. On two occasions, upon running to 100 hours, the support oil, on cooling to room temperature, solidified to a heavy gelatinous consistency. In both cases the roller bearings in the gear machine were damaged and had to be replaced. Of the several oils considered for use as a support oil, none have shown any improvement in thermal stability above that of the oil which is presently being used. The use of oils with better high-temperature (400°F) characteristics and satisfactory gear load-carrying capacity is currently prohibitive due to the high cost of these oils at this time.

3. Standard 165°F Support Oil System

The use of induction heating to heat the test gears in the high-temperature load-carrying capacity studies has afforded a return to the standard 165°F support oil system described previously.[10.01] Apart from the lubrication function, the 165°F support oil is also used as a control coolant in maintaining the test gear temperature by carrying away excess heat from the gear machine bearings and shafts.

4 High-Temperature Test Gears

For the work described herein, special test gears of the same principal dimensions as the standard Ryder test gears, but conforming to SwRI design with respect to tooth width, were used. During the previous contractual period, tests were completed using the SwRI high-temperature test gears made of through-hardened M-50 steel.[0.85] However, the frequent tooth breakage under moderate to heavy loads has precluded the use of the through-hardened M-50 steel test gears as reliable test specimens.

In the present contractual period, test gears of SwRI design made of Nitralloy N steel were used. In addition, Nitralloy N steel test gears of another design, which will be referred to as "Design X," were received from WADD. These gears were also included in the present program.

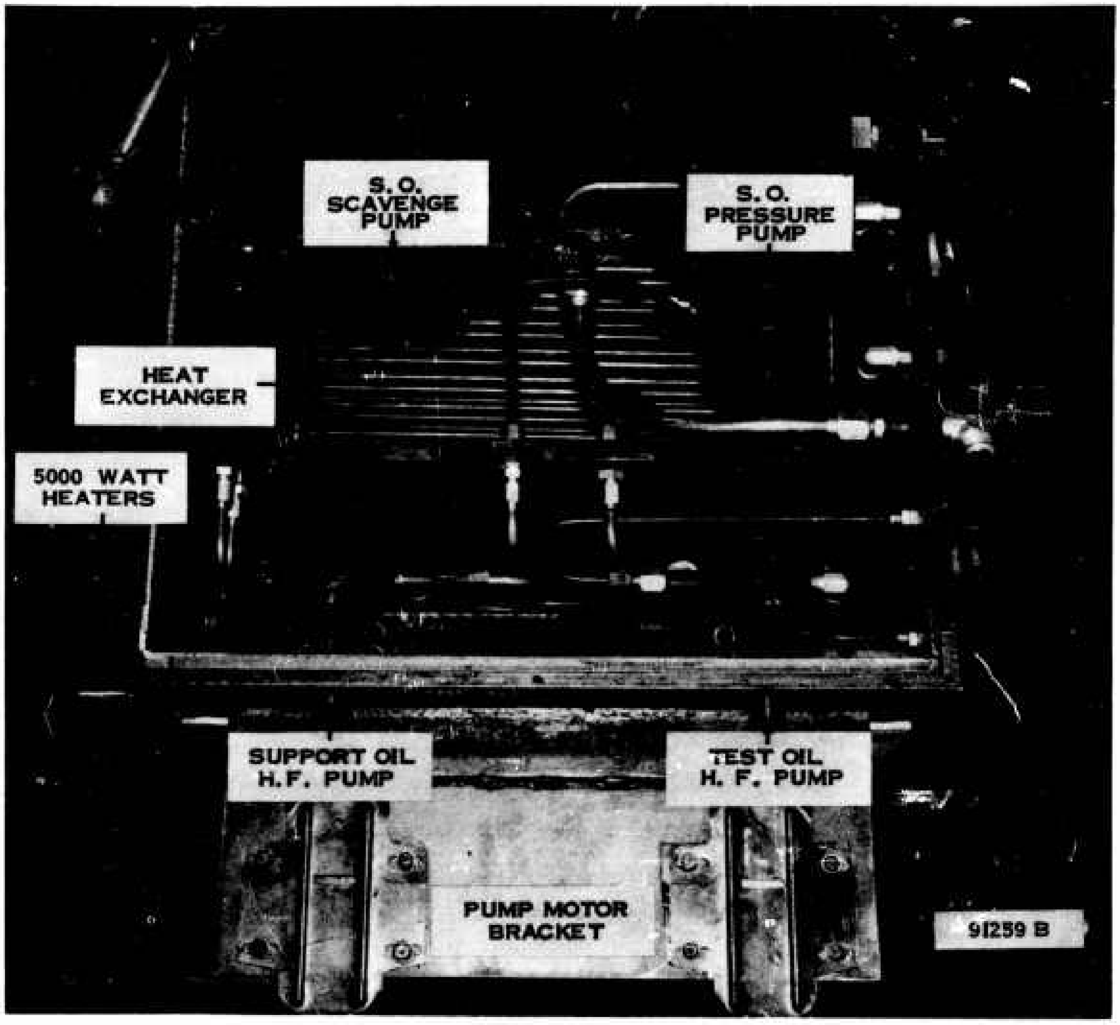


FIGURE 6. HIGH-TEMPERATURE SECTION OF DUAL-TEMPERATURE SUPPORT OIL SYSTEM

The principal dimensions of the high-temperature test gears are shown in comparison with those of the standard Ryder test gears in Table 1. In Table 1, the case hardness is given in Rockwell 15 N units and the core hardness is given in Rockwell C units, the usual units of these measurements.

5. Induction Heating of Test Gears

In the 400°F load-carrying capacity tests in which the 400°F test gear temperature was obtained by induction heating, the gear blank temperature was measured and the induction heating controlled by use of a model R-4D1 radiometer in conjunction with a strip chart recorder-controller. A schematic diagram of this system is shown in Figure 7. Before each test, the radiometer output is checked against a calibration standard. This calibration standard and procedure are described in a later section. The operation of this system has been such that gear blank temperatures have been accurately measured and controlled to within ± 15°F over a temperature range of 165 to 700°F.

The advantages of induction heating as a method of heating the test gears in gear lubrication studies are, from an operational standpoint, manifold. For example, the difficulties encountered with a high-temperature support oil system would be eliminated. These include the time normally required to heat the support oil and gear machine to test temperatures, excessive support oil deterioration due to the required high support oil temperature, increased wear of pumps and other mechanical parts due to the high temperatures, the time required to clean the entire support oil system after each 80 hours of operation, and a personnel safety hazard due to the high pressures maintained in the high-temperature section of the support oil system.

6. Temperature Measurement by Infrared Radiometry

A Barnes R-4D1 industrial radiometer was used to measure the gear-blank temperature of the narrow test gear during operation. This instrument measures the infrared radiation from the test gear. This measurement of radiation can be related to temperature by means of calibration against thermocouple readings. During the reporting period, several calibration runs were made, and these will be discussed in the following paragraphs.

First, the instrument was calibrated in a mock-up of the gear machine, using a used standard Ryder test gear which was heated by means

TABLE i. COMPARISON OF PRINCIPAL DIMENSIONS OF STANDARD RYDER TEST GEARS WITH HIGH-TEMPERATURE TEST GEARS

	Standard Ryder Test Gears	High-Temperature Test Gears: M-50 Steel, SwRI Design	High-Temperature Test Gears: Nitralloy N Steel, SwRI Design	High-Temperature Test Gears: Nitralloy N Steel, Design X
Pitch Diameter, in.	3.500	3.500	3.500	3.500
Face Width, Narrow Gear, in.	0.250	0.250	0.250	0.250
Face Width, Wide Gear, In.	0.937	0.375	0.375	0.375
Number of Teeth	28	28	28	35
Diametral Pitch	8	8	8	10
Pressure Angle, degree	22.5	22.5	22.5	20
Tip Relief	None	None	None(a)	None
Material	AMS-6260	M-50	Nitralloy N	Nitralloy N
Case Hardness, Rockwell 15N	90-92	90-92	90-92	92-94
Case Thickness, in.	.025-.040	Through-hardened	0.018-0.024	0.018-0.024
Core Hardness, Rockwell C	30-40	Through-hardened	30-40	38-44
Surface Finish, rms, in.	$20-35 \times 10^{-6}$	$20-35 \times 10^{-6}$	$20-35 \times 10^{-6}$	20×10^{-6} (Max.)

(a) Ten sets of SwRI design Nitralloy N gears were obtained with 0.0015 in. tip relief for gear fatigue investigations.

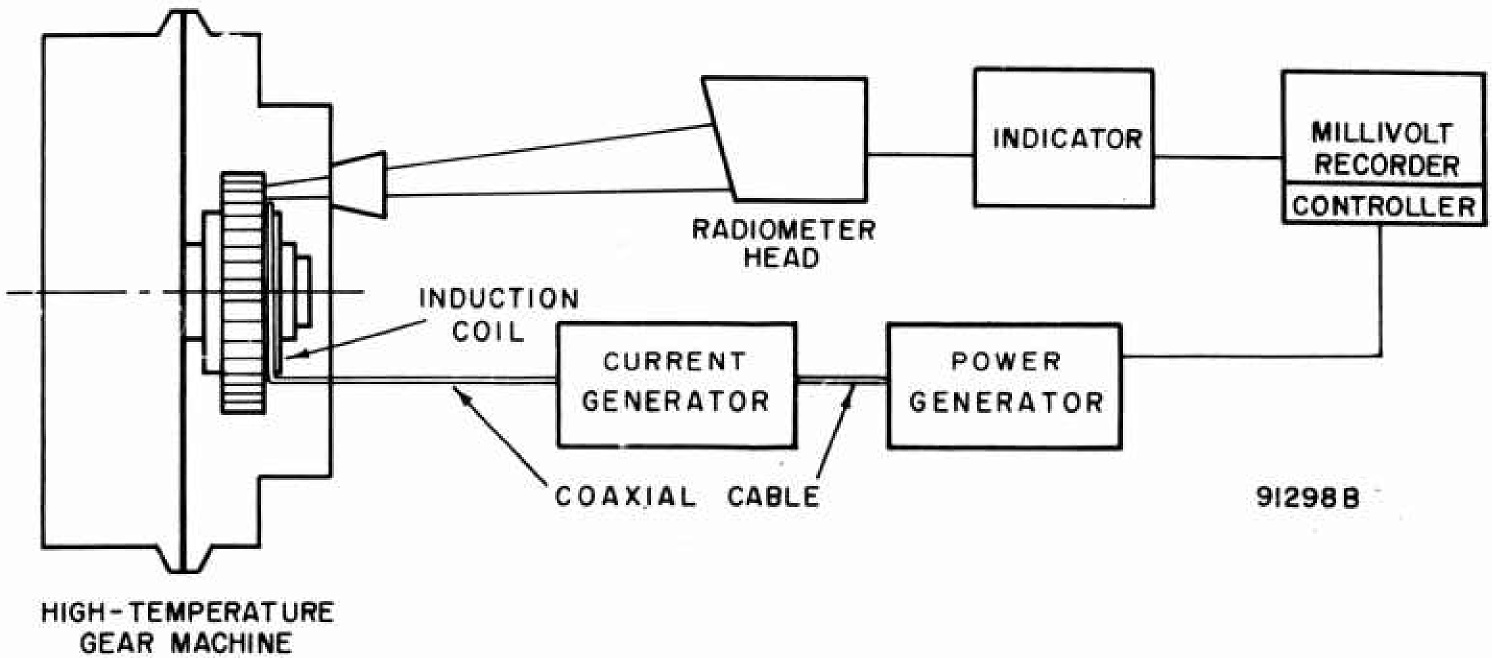


FIGURE 7. GEAR-BLANK TEMPERATURE MEASUREMENT AND INDUCTION HEATING CONTROL SYSTEM

of a cartridge heater welded to the gear. The instrument was focused on the gear at an angle such that portions of the side and face of a single tooth were included in the surface area "seen" by the instrument. A thermocouple was placed in the tooth such that the temperature indicated would serve as a calibration standard. The calibration was then repeated in a WADD high-temperature gear machine, using another used standard Ryder test gear heated by an induction heater. In both instances, the calibration was made with the test gear both remaining dry and wetted with a lubricant. Identical calibration curves were obtained in both configurations, with the gear both dry and wetted.

After the calibration of the radiometer was established, measurements of gear-blank temperature were made in the actual load-carrying capacity tests. It was found that there was a continuous shift of the radiometer calibration as the test gear, which was new to begin with, progressively became darkened during test. In order to verify this progressive change, the calibration was repeated in a WADD high-temperature gear machine, using a new test gear heated through the range of 300 to 800 °F by induction heating. Figure 8 shows the results obtained from several heating cycles. On each successive heating of the gear, it can be seen that there was an increase in radiometer output at any given temperature as read by the thermocouple. It was determined that the shift of the radiometer calibration curve was caused by a change in the emissivity of the gear, due to the fact that the physical appearance of the test gear changed from a bright polished finish to a dark dull state upon being heated. Since the first studies were made with a used and considerably darkened gear, no substantial change in emissivity had been encountered. From this experience, it was concluded that only when the gear emissivity approached that of a black body would constant or reproducible results be obtained.

To insure that black body radiation was obtained at all times, a black chromium ring was electroplated on the web of each side of the narrow test gear as a standard practice. This is shown in Figure 9. The electroplating process is very simple and inexpensive, and the gear can be plated in the laboratory by using a 1000-ml glass beaker for the plating vat and a storage battery for current.

In view of the aforementioned difficulties, it was evident that a thorough investigation of the infrared emission characteristics of the gear materials used in the test program was needed. An apparatus was designed such that a gear could be heated throughout to an even and constant temperature, as shown in Figure 10. This apparatus consisted of two steel blocks so machined that when a gear was placed between them, a form fit on the gear was obtained. The apparatus was heated by cartridge heaters placed

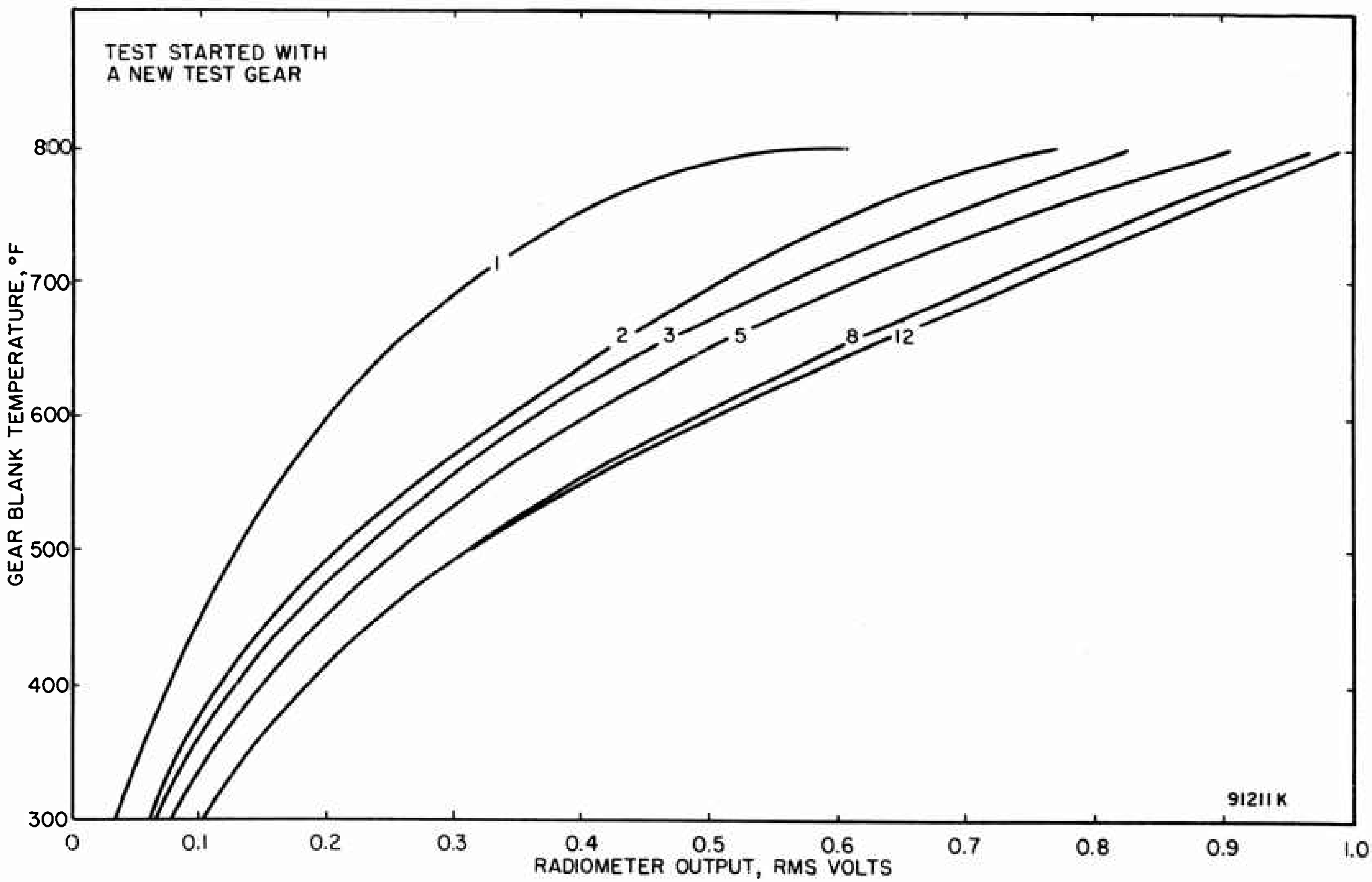


FIGURE 8. RADIOMETER CALIBRATION SHOWING PROGRESSIVE EMISSIVITY CHANGE OF TEST GEAR

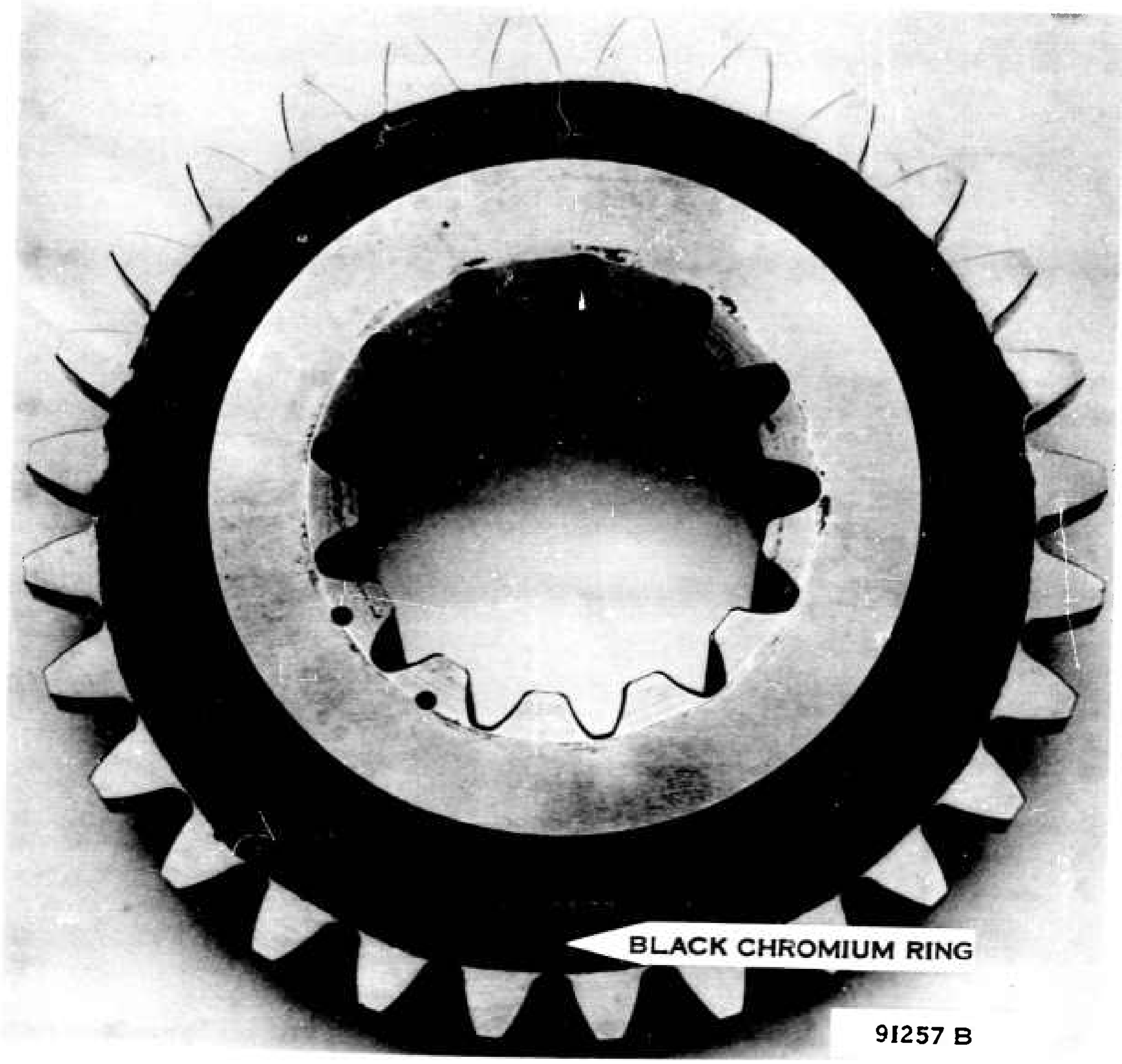


FIGURE 9 NARROW TEST GEAR WITH BLACK CHROMIUM RING ON WEB

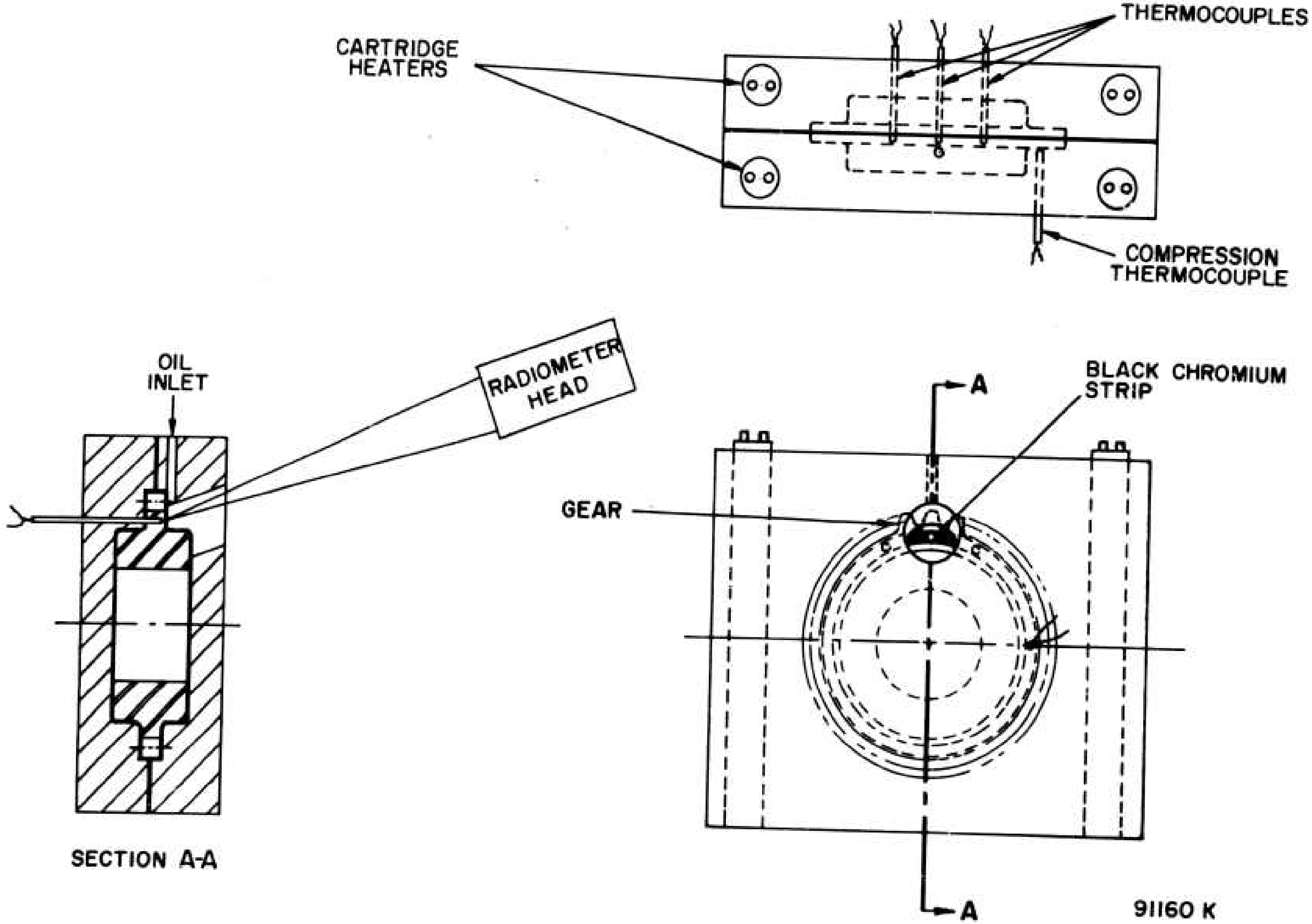


FIGURE 10. RADIOMETER CALIBRATION APPARATUS

in the steel blocks as shown. The radiometer was focused on the plated portion of the gear through a hole in the block. Oil could be placed on the gear through a small vertical hole in the block. The oil was heated by the block before coming into contact with the gear, thereby preventing any cooling effect.

Temperature measurements were made on plated AMS 6260, M-50, and Nitralloy N steel test gears while the gears were being heated in the above apparatus. No plating of the Design X gear was required since this gear had a black finish when received. Thermocouples were fitted into the web of the gear from the side opposite the point at which the radiometer was focused, and to a depth such that they were within 1/32 in. of the face of the web. With the gear in place, the thermocouple leads were taken out through ceramic insulators fitted into the back block. In addition, a thermocouple was fitted into the front block such that when the gear was in place, the thermocouple was in compression with the gear near the point at which the radiation was measured. Thermocouple and radiometer output data were taken during several heating cycles from 350 to 750°F on each of the gears. The results are shown in Figure 11. From these data it can be seen that the calibration of all gear materials used was the same within about ± 15°F over the entire temperature range.

To insure that identical calibration is obtained at all times, the apparatus shown in Figure 10 has since been adopted as a calibration standard. The apparatus may be attached to either of the two WADD high-temperature gear machines, in such a way that rapid checks of the radiometer output can be made at any time while gear-blank temperature measurements are being made during test.

7. Closed-Circuit Television for Gear Inspection

To insure safety of the operating personnel from exposure to high-temperature parts and toxic lubricant fumes, it is now standard practice at SwRI to locate all high-temperature test rigs in individual test cells that are well-ventilated, and to perform as many of the controlling and inspection operations as possible from outside the test cells. The closed-circuit television method for gear inspection previously described(0.85) has been adopted for general use in gear lubrication experiments at SwRI, and approximately 160 scuff ratings have been obtained with this method. During a number of such tests, checks of the television ratings were made by the visual-microscopic method.

In an effort to determine the accuracy of the scuff ratings obtained using closed-circuit television, three operators and two engineers

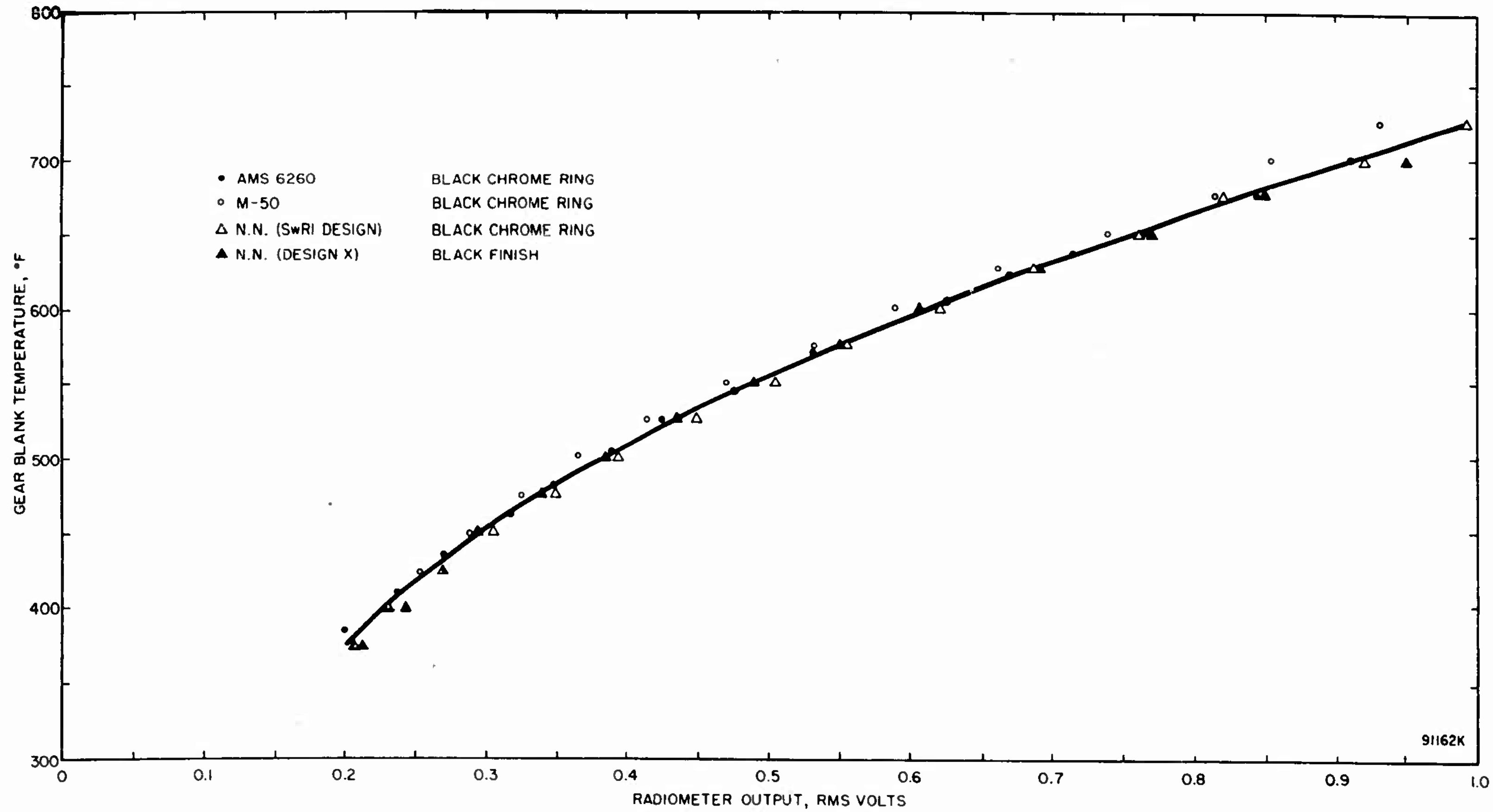


FIGURE 11. RADIOMETER CALIBRATION FOR SEVERAL GEAR MATERIALS

made individual ratings of a used test gear, first by television and then by the visual-microscopic method. The results of the experiment are shown in Table 2. It can be seen from the data presented that the scuff ratings obtained by the television method are well within the normal accuracy of visual-microscopic ratings. Photographs of the television presentation, made with a Polaroid Land camera, are shown in Figure 12.

8. Measurement and Control of Load Oil System Pressure

In an effort to obtain better hydraulic load oil pressure control, the hand-operated needle valve control system has been replaced by a Tel-O-Set recorder-controller system manufactured by the Minneapolis-Honeywell Regulator Company. The use of this system has afforded automatic setting and control of the load oil pressure to within ± 0.25 psi over a range of 0 to 120 psig. A schematic diagram of the system is shown in Figure 13. The simplicity of operation is such that the operator is required only to set the pressure-set-control to the load oil pressure desired; after a few seconds of delay, the load is automatically changed to the preset value and recorded, requiring no further attention from the operator until the end of the run period. The rate of load application is constant for any one load setting and is independent of the operator.

Prior to being put into operation, the load control system was calibrated against a calibrated pressure gage. Figure 14 is a section of the recorder chart showing 10-psi controlled load increments in comparison with pressure gage measurements. It can be seen that the recorded pressures were within an estimated 0.1 to 0.25 psi of the pressure gage readings. Satisfactory operation has been obtained with this system.

C. Investigations of Gear Load-Carrying Capacity

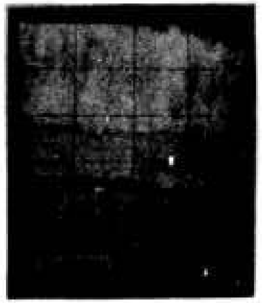
The investigation of gear load-carrying capacity has included a study of results obtained from the standard Ryder gear machine at 165°F and from the WADD high-temperature gear machine at 165 and 400°F, in order to establish a base line for comparison of results obtained with the two machine types.

Representative lubricants have been evaluated on test gears fabricated from AMS 6260, M-50 and Nitralloy N steel, in order to compare the effect of these lubricants on the various gear materials. In addition, these same lubricants were run on gears designed to conform with the geometry of gears being used in one model of advanced gas turbine engine and fabricated from Nitralloy N steel (Design X), in order to establish comparative values between the standard test gear design and the gear design used in a production model gas turbine.

TABLE 2. COMPARISON OF VISUAL-MICROSCOPIC AND TELEVISION RATINGS

	Tooth Scuff, %									
	Operator								Engineer	
	No. 1		No. 2		No. 3		No. 4		No. 1	No. 2
No.	V. M.	T. V.	V. M.	T. V.	V. M.	T. V.	V. M.	T. V.	T. V.	T. V.
1	75	75	75	75	75	75	75	75	75	75
2	75	70	80	80	75	75	75	70	75	75
3	65	60	60	60	60	60	60	65	60	60
4	70	65	70	70	70	65	65	60	70	70
5	30	25	30	30	30	30	35	30	30	30
6	65	70	65	70	60	65	65	65	65	60
7	50	50	55	50	55	50	55	55	55	50
8	35	35	40	35	35	35	30	30	40	40
9	45	45	50	45	50	40	50	45	40	45
10	50	50	60	65	55	50	60	60	50	50
11	55	60	60	60	55	60	60	55	60	60
12	60	65	65	65	55	65	65	60	60	55
13	60	60	60	60	55	55	55	55	55	50
14	40	40	45	50	45	40	40	40	40	40
15	30	35	30	30	30	35	30	30	30	30
16	65	65	60	70	60	60	65	70	65	65
17	70	65	70	70	65	65	70	65	65	65
18	35	40	35	40	35	35	40	35	35	35
19	60	65	60	60	60	65	60	65	65	60
20	65	65	60	60	60	60	65	65	70	65
21	75	75	75	80	75	70	70	75	75	75
22	75	75	75	80	75	75	75	80	75	75
23	75	75	75	80	75	75	75	75	80	75
24	75	70	70	70	65	70	70	70	75	75
25	60	65	60	60	65	55	60	55	60	60
26	70	65	60	60	60	60	65	70	65	65
27	75	75	75	70	75	75	75	80	70	70
28	60	60	55	60	50	55	60	60	50	50
Average	59.5	59.5	59.8	60.9	58.0	57.9	59.6	59.3	59.1	58.0

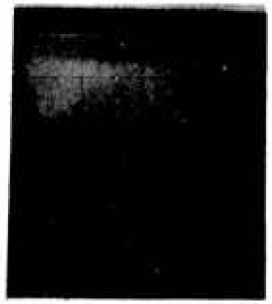
	V. M.	T. V.
	59.5	59.5
	59.8	60.9
	58.0	57.9
	59.6	59.3
		59.1
		58.0
Average	59.2	59.1



75% SCUFF

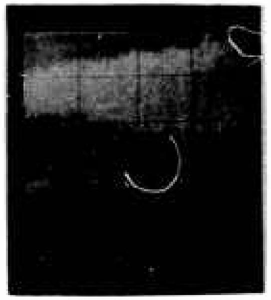
60% SCUFF

30% SCUFF



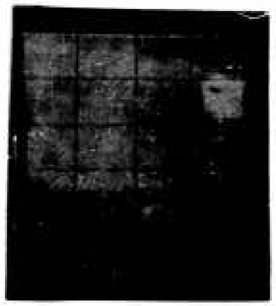
55% SCUFF

40% SCUFF

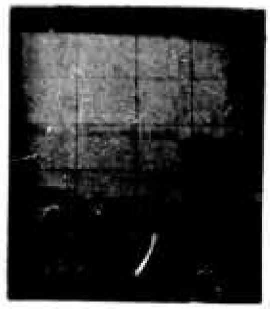


60% SCUFF

55% SCUFF

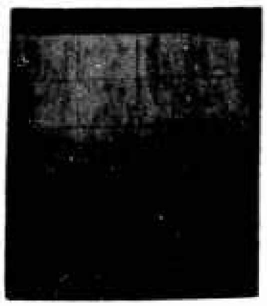


30% SCUFF



65% SCUFF

65% SCUFF



75% SCUFF

80% SCUFF

60% SCUFF

70% SCUFF

FIGURE 12. PHOTOGRAPHS OF TELEVISION PRESENTATION OF GEAR SCUFF

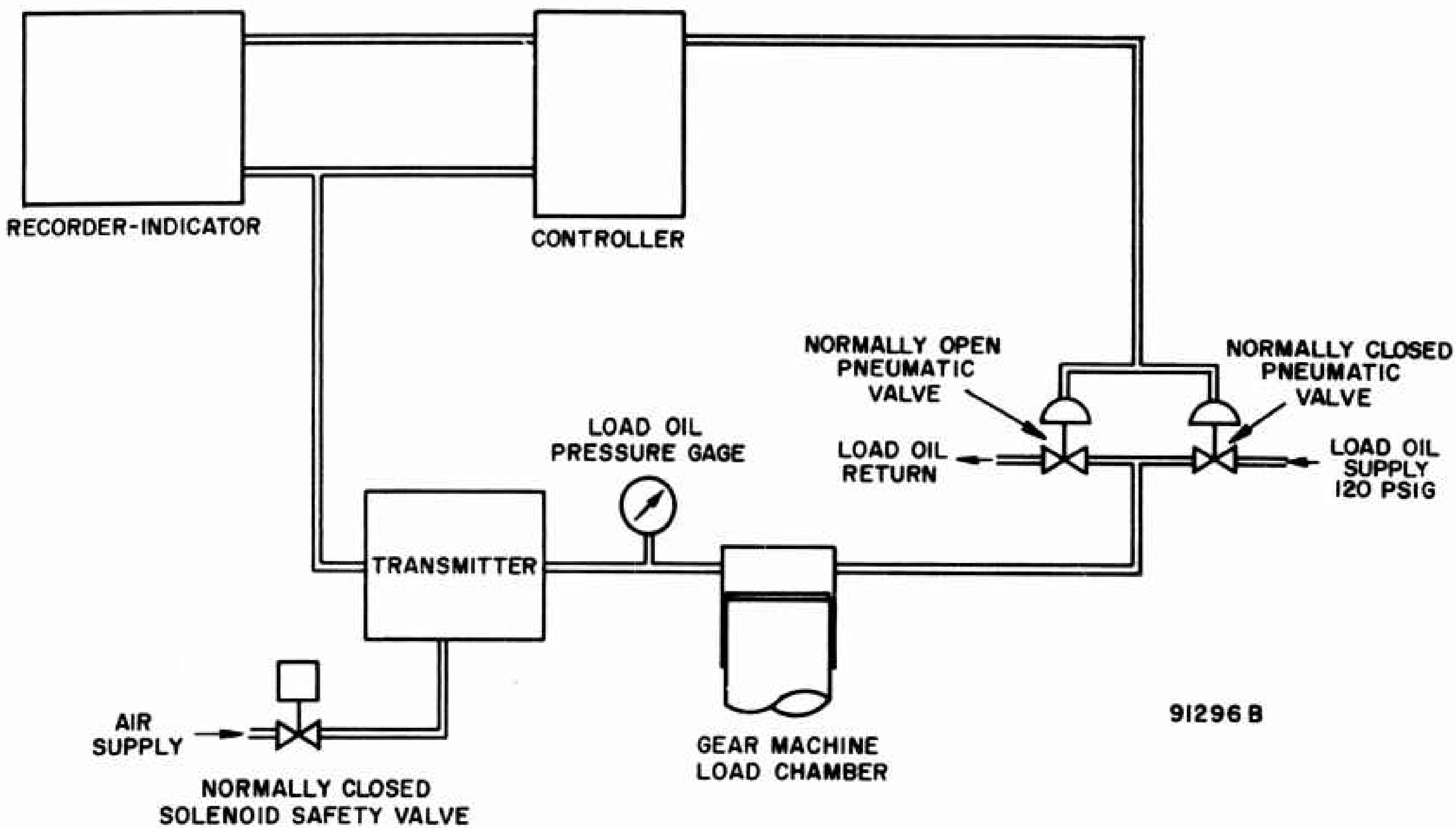


FIGURE 13. LOAD OIL PRESSURE AUTOMATIC RECORDER-CONTROLLER SYSTEM

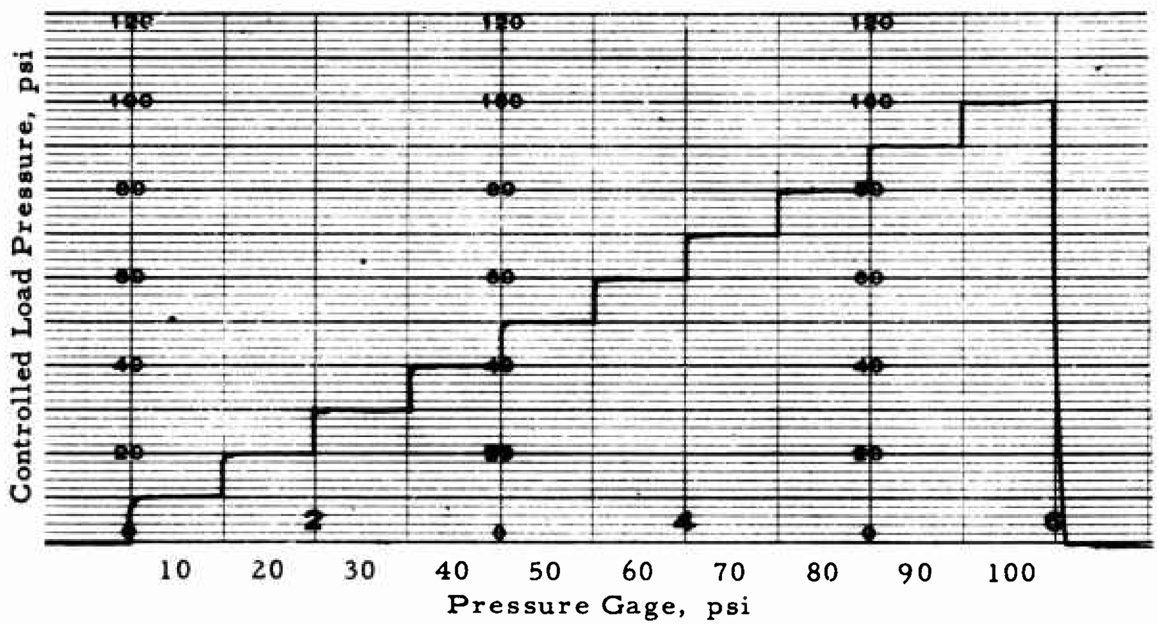


Chart Speed, 9 In/Hr

91297 B

FIGURE 14. CALIBRATION OF LOAD OIL PRESSURE CONTROL SYSTEM

The work on the standard Ryder test gears and the M-50 steel test gears was completed during the previous contract.(0.85) The work on Nitralloy N steel test gears of two different designs was carried out during the present contract period. Because of the limited supply of the M-50 and Nitralloy N gears, the entire program was somewhat limited in scope. The bulk of the work was done at a lubricant temperature of 400°F; only a limited number of tests were made at 165°F lubricant temperature, for the purpose of comparison.

All of the 400°F tests were made using the two WADD high-temperature gear machines available at SwRI. The test method employed followed closely Federal Test Method 6508, except for the use of a different test machine, changes in test gears as required, and changes in temperature conditions as required. A comparison of the various test methods is presented in Table 3. In addition to these tests, a very limited number of tests were also made at a different lubricant flow rate, with other conditions held the same as those indicated in the appropriate columns of Table 3. Note further from Table 3 that, although the same load-increment step of 5 psi load oil pressure was used in all tests, the corresponding tooth load obtained in the WADD high-temperature gear machine is 230 lb/in., as compared with 370 lb/in. obtained in the standard Ryder gear machine.

A summary of the results obtained with standard Ryder test gears, at lubricant temperatures of 165°F and 400°F, is presented in Table 4. The bulk of these results were obtained during the previous contract period. However, for the sake of completeness, the earlier results are tabulated together with those obtained during the present reporting period. Table 5 presents the summary of the results obtained with Nitralloy N steel test gears of SwRI design, and Table 6 presents the results obtained with Nitralloy N steel test gears of Design X. As noted previously, most of the work reported in Tables 5 and 6 was conducted at 400°F lubricant temperature. It should be mentioned that for those tests reported in Tables 4, 5 and 6 where the used oil analysis is given, that the test oil was not changed after each determination but was reused until the neutralization number of the oil reached 1.0 mg KOH/g as directed by WADD.

1. Test Precision and Rating Level

Before discussing the results of the scuff-limited load determinations, it is proposed to examine the repeatability and reproducibility, as well as the rating level, of the 165°F and 400°F load-carrying capacity tests using the WADD high-temperature gear machine. It is believed that an examination of these factors, in the light of the attainments of the standard load-carrying capacity test using the standard Ryder gear machine, will aid in the proper interpretation of the experimental

TABLE 3. COMPARISON OF LOAD-CARRYING CAPACITY TEST METHODS

	Federal Test Method 6508	Methods Used in Present Program	
		165°F Test	400°F Test
Test Machine	Erdco-Ryder gear machine	WADD high-temperature gear machine	WADD high-temperature gear machine
Test Gears	Ryder test gears	As required	As required
Operating Conditions			
Test gear speed, rpm	10,000 ± 100	10,000 ± 100	10,000 ± 100
Test oil flow rate, ml/min (exit lubrication)	270 ± 5	270 ± 5	270 ± 5
Test oil-in temperature, °F	165 ± 5	165 ± 5	400 ± 5
Support oil-in temperature:			
High-temperature section, °F	165 ± 5	165 ± 5	400 ± 10
Low-temperature section, °F	---	---	165 ± 10
Method of Loading			
Increment steps in tooth load (corresponding to 5-psi steps in load oil pressure), lb/in.	370	230	230
Duration of load-increment steps, min	10	10	10
Criterion of Lubricant Rating	Tooth load at which 22.5% of working tooth area is scuffed	Tooth load at which 22.5% of working tooth area is scuffed	Tooth load at which 22.5% of working tooth area is scuffed

TABLE 4. RESULTS OF TESTS WITH STANDARD RYDER TEST GEARS

	165°F Test						400°F Test					
	Scuff-Limited Load. lb/in. (a)		Test Oil at End of Test				Scuff-Limited Load, lb/in. (a)		Test Oil at End of Test			
			Vis at 100°F		Neut. No.				Vis at 100°F		Neut. No.	
Oil Code	A	B	A	B	A	B	A	B	A	B	A	B
Reference "B"	2540	2540	-	-	-	-	2000	1910	-	-	-	-
	2850	2500	-	-	-	-	2580	1820	-	-	-	-
	2660	2720	-	-	-	-						
	2860	2650	-	-	-	-						
	2260	2260	-	-	-	-						
	3160	2780	-	-	-	-						
	3380	2850	-	-	-	-						
	2720						2080					
GTO-313	2090	2310	-	-	-	-	1620	1620	-	-	-	-
	1850	1740	-	-	-	-	1550	1950	-	-	-	-
	2600	2330	-	-	-	-						
	2600	2480	-	-	-	-						
	2250						1690					
GTO-770	4700	4090	-	-	-	-	1740	1220	-	-	-	-
Init. Vis/100°F = 64.6	4880(a)	4470(a)	78.6	66.7	0.04	0.04	2660	2330	-	-	-	-
Init. N. N. = 0.08							3020	3020	-	-	-	-
	4540						2330					
GTO-790	2650	2540	-	-	-	-	410	410	-	-	-	-
	2180	2560	-	-	-	-	400	1060	-	-	-	-
							890	480	-	-	-	-
							1110	1250	-	-	-	-
	2480						750					
GTO-794(c)	3280	2970	-	-	-	-	1820(a)	2170(a)	-	-	-	-
	3060	3250	-	-	-	-	1110(a)	770(a)	-	-	-	-
							700(a)	730(a)	-	-	-	-
							1370(a)	1310(a)	-	-	-	-
	3140						1250					
GTO-803(c)	2850(a)	(b)	-	-	-	-	590(a)	810(a)	-	-	-	-
Init. Vis 100°F = 34.4	3250(a)	3360(a)	-	-	-	-						
Init N N = 0.02	2980(a)	2640(a)	43.1	35.3	0.11	0.10						
	2860(a)	2420(a)	35.2	35.1	0.11	0.14						
	2910						700					
GTO-855	2480(a)	2420(a)		-	-	-	880(a)	460(a)	-	-	-	-
Init. Vis 100°F = 29.0	2260(a)	2050(a)	28.9	29.1	0.10	0.12	870	680	29.8	31.2	0.30	0.38
Init N. N. = 0.07	2050(a)	2420(a)	28.6	29.2	0.14	0.10						
	2280						720					
GTO-861(d)	2220(a)	1930(a)	-	-	-	-	370(a)	390(a)	-	-	-	-
	2080						380					
GTO-885-1(d)	2000(a)	1930(a)	-	-	-	-	370(a)	420(a)	-	-	-	-
	1970						400					
GTO-915(d)	1850(a)	1740(a)	-	-	-	-						
Init Vis/100°F = 16.0	2010(a)	1880(a)	16.2	16.2	0.09	0.08						
Init. N. N. = 0.04	1930(a)	1770(a)	16.0	16.1	0.06	0.09						
	1580(a)	1780(a)	16.7	16.0	0.06	0.06						
	1820											
GTO-882(e)	2010(a)	1780(a)	-	-	-	-	1230(a)	1180(a)	-	-	-	-
	1900						1210					
GTO-939(e)	2230(a)	2230(a)	15.2	15.2	0.06	0.05	720	370	15.5	15.6	0.15	0.63
Init. Vis/100°F = 15.1							300	420	15.4	15.6	0.12	0.11
Init. N. N. = 0.04												
	2230						450					
LRO-11	2060(a)	2200(a)	70.8	71.0	0.00	0.00	630	680	83.7	71.3	0.02	0.03
Init. Vis/100°F = 70.9	1940(a)	2080(a)	70.3	71.0	0.00	0.00	630	720	70.0	70.0	0.02	0.04
Init. N. N. = 0.00												
	2070						670					
LRO-13	2610(a)	2810(a)	365.6	365.9	0.00	0.00	910	1280	355.7	361.5	0.03	0.03
Init. Vis/100°F = 368.0	2310(a)	2380(a)	365.0	365.1	0.01	0.00	1160	650	363.9	361.8	0.04	0.04
Init. N. N. = 0.00												
	2530						1000					

(a) WADD high-temperature gear machine No. 2 used for tests marked by (a). WADD high-temperature gear machine No. 1 used for all other tests.
(b) "B" side not run.
(c) Different batches of same formulation.
(d) Different batches of same formulation.
(e) Different batches of same formulation.

TABLE 5. RESULTS OF TESTS WITH NITRALLOY N STEEL TEST GEARS OF SwRI DESIGN

Oil Code	165°F Test: Scuff-Limited Load, lb/in. (a) A	B	Test Oil at End of Test: Vis at 100°F A	B	Neut. No. A	B	400°F Test: Scuff-Limited Load, lb/in. (a) A	B	Test Oil at End of Test: Vis at 100°F A	B	Neut. No. A	B
Reference "B"							>5600	>5600	-	-	-	-
							>5600	>5600	-	-	-	-
							>5600					
GTO-313							2340	4310	-	-	-	-
							3080	2840	-	-	-	-
							1560	1520	-	-	-	-
							1270	1970	-	.	-	-
							2360					
GTO-770	5740(a, b)	5720(a, b)	66.4	65.1	0.04	0.04	4580	4710	60.3	58.2	0.06	0.06
Init. Vis/100°F = 64.6							3810	4220	58.3	58.7	0.06	0.06
Init. N. N. = 0.08							3940	4670	60.1	59.8	0.05	0.06
	5730						4320					
GTO-803(c)							1280	1140	37.3	39.4	1.47	2.50
Init. Vis/100°F = 34.4							1990	1400	37.3	39.2	1.50	2.50
Init. N. N. = 0.02							1130	940	42.4	40.9	3.43	4.51
							1310					
GTO-855	2440(a)	2560(a)	30.9	32.1	0.35	0.49	1240	1080	-	-	-	-
Init. Vis/100°F = 29.0	2530(a)	2520(a)	33.3	30.9	0.75	0.18	790	1030	-	-	-	-
Init. N. N. = 0.07							1330	1430	-	-	-	-
							1360	1220	-	-	-	-
	2510						1190					
GTO-915(d)	2000(a)	2480(a)	-	16.0	-	0.09	1450	1150	-	-	-	-
Init. Vis/100°F = 16.0	1870(a)	2010(a)	16.0	16.0	0.06	0.06	950	1090	-	-	-	-
Init. N. N. = 0.04	1790(a)	1740(a)	16.0	16.0	0.05	0.11	710	1670	16.8	16.6	0.40	0.50
							740	1150	16.6	16.7	0.37	0.21
	1980						1110					
GTO-882(e)							760	1090	-	-	-	-
							1170	1130	-	-	-	-
							1040					
GTO-939(e)	2400(a)	2280(a)	15.7	16.2	0.25	0.43	1340	1670	16.2	16.7	1.00	-
Init. Vis/100°F = 15.1	2320(a)	2340(a)	16.5	16.7	0.51	0.63	1540	1220	15.6	16.0	0.32	0.52
Init. N. N. = 0.04												
	2340						1440					
LRO-11(f)							1280	1310	70.2	70.6	0.00	0.00
Init. Vis/100°F = 70.9	2360(a)	1770(a)	69.5	82.2	0.04	0.04	1520	1400	70.7	70.0	0.00	0.00
Init. N. N. = 0.00	2490(a)	2330(a)	83.4	70.6	0.03	0.03	840	1500	70.2	71.0	0.00	0.00
							1250	1510	70.4	70.9	0.00	0.00
	2240						1330					
LRO-13	2860(a)	3050(a)	369.2	370.0	0.01	0.01	1620	1720	366.4	369.0	0.02	0.02
Init. Vis/100°F = 368.0	2520(a)	2870(a)	367.7	367.7	0.01	0.01	1430	1640	367.9	368.8	0.02	0.02
Init. N. N. = 0.00							1760	1880	368.6	370.8	0.02	0.03
							1710	1410	369.3	367.4	0.02	0.02
	2830						1650					

(a) WADD high-temperature gear machine No. 2 used for tests marked by (a). WADD high-temperature gear machine No. 1 used for all other tests.
(b) Extrapolated value.
(c) A different batch of GTO-794.
(d) A different batch of GTO-861.
(e) Different batches of same formulation.
(f) A different batch of LRO-8.

TABLE 6. RESULTS OF TESTS WITH NITRALLOY N STEEL TEST GEARS OF DESIGN X

Oil Code	165°F Test: Scuff-Limited Load, lb/in. (a) A	B	Test Oil at End of Test: Vis at 100°F A	B	Neut. No. A	B	400°F Test: Scuff-Limited Load, lb/in. (a) A	B	Test Oil at End of Test: Vis at 100°F A	B	Neut. No. A	B
Reference "B"							4610(b)	(c)	-	-	-	-
							4570(b)	(c)	-	-	-	-
							4630(b)	(c)	-	-	-	-
							4600					
GTO-313							2690	2810	-	-	-	-
							2380	3160	-	-	-	-
							2880	(c)	-	-	-	-
							2780					
GTO-770							>3000	(c)	61.4	-	0.05	-
Init. Vis 100°F = 64.6							>3000	(c)	61.5	-	0.06	-
Init. N. N. = 0.08							3950(b)	(c)	59.9	-	0.07	-
							3950					
GTO-803 (d)							3260	(c)	40.8	-	2.71	-
Init. Vis 100°F = 34.4							2660	(c)	39.8	-	1.71	-
Init. N. N. = 0.02							2900	3890(b)	39.1	38.6	1.83	0.73
							4270	(c)	40.7	-	1.30	-
							3440	(c)	39.8	-	0.90	-
							3400					
GTO-855							2290	2390	-	-	-	-
Init. Vis 100°F = 29.0							2340	2290	-	-	-	-
Init. N. N. = 0.07							2630	2660	32.6	31.3	0.97	0.47
							2430					
GTO-915(e)	2390	2100	16.0	15.9	0.07	0.07	2230	2330	-	-	-	-
Init. Vis 100°F = 16.0	2340(a)	2290(a)	16.0	16.0	0.09	0.08	2230	1950	-	-	-	-
Init. N. N. = 0.04	2280(a)	2310(a)	15.8	15.8	0.09	0.09	2380	2430	17.3	16.8	0.56	0.36
	2280						2260					
GTO-939(f)	2390	2390	15.8	15.2	0.07	0.07	1850	1830	15.5	15.8	0.28	0.41
Init. Vis 100°F = 15.1							2230	1800	15.7	15.8	0.39	0.33
Init. N. N. = 0.04							1780	1850	15.9	16.3	0.50	0.60
	2390						1890					
LRO-11(g)							2710	2250	70.6	70.3	0.02	0.02
Init. Vis/100°F = 70.9							2470	2360	69.1	69.4	0.02	0.02
Init. N. N. = 0.00							2400	2110	71.3	71.0	0.01	0.01
							2380					
LRO-13							2950	3140	368.5	372.4	0.01	0.00
Init. Vis/100°F = 368.0							3330(b)	(c)	372.4	-	0.00	-
Init. N. N. = 0.00							3100	(c)	372.6	-	0.00	-
							3130					

(a) WADD high-temperature gear machine No. 2 used for tests marked by (a). WADD high-temperature gear machine No. 1 used for all other tests.
(b) Extrapolated value.
(c) "B" side not run because of gear tooth breakage during "A" side run.
(d) A different batch of GTO-794.
(e) A different batch of GTO-861. (See Table 3.)
(f) A different batch of GTO-882.
(g) A different batch of LRO-8.

results. It should be emphasized that the data collected to date on the WADD high-temperature machine are by no means extensive. However, they are sufficient to provide a fairly realistic indication of the precision and accuracy that have been attained.

The scuff-limited loads of three lubricants (Reference "B," GTO-313, and GTO-790) at 165°F lubricant temperature were previously compared[0.85] on the basis of tests performed using three standard Ryder gear machines and two WADD high-temperature gear machines available at SwRI. Additional data have been obtained on one high-load lubricant (GTO-770) at 165°F. Table 7 presents a summary of these data including the results previously reported. It will be noted that the rating level of the two high-temperature gear machines appears to remain similar, and practically the same as that of the standard Ryder gear machines.

In Tables 4, 5 and 6, the individual scuff-limited load values are given for a number of lubricants in 165°F tests and 400°F tests, using the WADD high-temperature machines. As noted in these tables, several of the lubricants, while they are coded differently, are actually different batches of the same formulations. It will be observed from the data furnished that the ratings obtained for any single lubricant, or for different batches of any given lubricant, are all generally quite consistent.

To aid in a quantitative evaluation of test repeatability, the data presented in Tables 4, 5 and 6, as well as the previous data on M-50 steel test gears[0.85], are analyzed and compared in Tables 8, 9 and 10. In these tables, the data for different batches of the same lubricant formulations have been combined. Table 8 gives the average scuff-limited load values. Table 9 presents information on test repeatability, and Table 10 presents information on test repeatability expressed as a fraction of the average scuff-limited load. From previous data, it is known that the fractional repeatability standard deviation of the standard 165°F load-carrying capacity test using the standard Ryder gear machine is 0.09[1.01]. From Table 10, it is seen that the fractional repeatability standard deviation of the 165°F load-carrying capacity test using the WADD high-temperature gear machine with standard Ryder test gears is also about 0.09. Although data on the other types of test gears at 165°F are rather limited, indications are that their fractional repeatability standard deviation is approximately the same as that obtained for the standard 165°F load-carrying capacity test.

The fractional repeatability standard deviation of the 400°F load-carrying capacity test using the WADD high-temperature gear machine with both the M-50 steel test gears and the Design X Nitralloy N steel test gears also appears to be approximately 0.09. However, an inferior

TABLE 7. COMPARISON OF SCUFF-LIMITED LOADS OBTAINED AT 165°F WITH STANDARD RYDER GEAR MACHINES AND WADD HIGH-TEMPERATURE GEAR MACHINES, USING STANDARD RYDER TEST GEARS

Test Machines	Scuff-Limited Load, lb/in.			
	Ref. B	GTO-313	GTO-770	GTO-790
Standard Ryder Gear Machines:				
Machine No. 4	2630(36)	2220(8)	---	---
Machine No. 5	2640(110)	2070(10)	---	2650(4)
Machine No. 6	2600(8)	---	4250(8)	---
WADD High-Temperature Gear Machines:				
Machine No. 1	2720(14)	2250(8)	4400(2)	2480(4)
Machine No. 2	2640(8)	---	4680(2)	---

The scuff-limited load given is the average of the number of determinations shown in parenthesis. Test conditions are as defined in Table 3.

TABLE 8. COMPARISON OF AVERAGE SCUFF-LIMITED LOADS OBTAINED BY SEVERAL LOAD-CARRYING CAPACITY TEST METHODS

Oil Code	Scuff-Limited Load, lb/in.[a]							
	Standard Ryder Test Gears (AMS 6260 Steel)		SwRI Design H. T. Test Gears				Design X H. T. Test Gears (Nitralloy N Steel)	
			M-50 Steel		Nitralloy N Steel			
	165°F	400°F	165°F	400°F	165°F	400°F	165°F	400°F
Reference "B"	2720(14)	2080(4)	>5090(2)	>5300(2)	-	>5600(4)	-	4600(3)
GTO-313	2250(8)	1690(4)	4200(3)	4360(2)	-	2360(8)	-	2780(5)
GTO-770	4540(4)	2330(6)	>4800(3)	>5120(2)	5730(2)	4320(6)	-	3950(3)
GTO-790	2480(4)	750(8)	>4100(2)	4160(6)	-	-	-	-
GTO-794, 803	2990(11)	1140(10)	4950(5)	4540(4)	-	1310(6)	-	3400(6)
GTO-855	2280(6)	720(4)	3910(2)	4200(4)	2510(4)	1190(8)	-	2430(6)
GTO-861, 885-1, 915	1890(12)	390(4)	4270(4)	2200(2)	1980(6)	1110(8)	2280(6)	2260(6)
GTO-882, 939	2060(4)	700(6)	4590(2)	3750(2)	2340(4)	1240(8)	2390(2)	1890(6)
LRO-8, 11	2070(4)	670(4)	2510(2)	2750(2)	2240(4)	1330(8)	-	2380(6)
LRO-13	2530(4)	1000(4)	-	-	2830(4)	1650(8)	-	3130(4)

(a) The scuff-limited load given is the average of the number of determinations shown in parentheses. All tests performed using WADD high-temperature gear machines under test conditions defined in Table 3.

TABLE 9. COMPARISON OF REPEATABILITY STANDARD DEVIATIONS OF SEVERAL LOAD-CARRYING CAPACITY TEST METHODS

Oil Code	Repeatability Standard Deviation, lb/in.							
	Standard Ryder Test Gears (AMS 6260 Steel)		SwRI Design H. T. Test Gears				Design X H. T. Test Gears (Nitralloy N Steel)	
			M-50 Steel		Nitralloy N Steel			
	165° F	400° F	165° F	400° F	165° F	400° F	165° F	400° F
Reference "B"	297	297	-	-	-	-	-	-
GTO-313	307	156	-	-	-	951	-	254
GTO-770	303	664	-	-	10	355	-	-
GTO-790	180	339	-	390	-	-	-	-
GTO-794, 803	277	520	-	-	-	334	-	550
GTO-855	176	171	-	426	41	196	-	154
GTO-861, 885-1, 915	155	21	180	-	249	307	100	156
GTO-882, 939	186	378	-	-	44	263	-	154
LRO-8, 11	92	38	-	-	276	210	-	186
LRO-13	166	242	-	-	191	150	-	135

TABLE 10. COMPARISON OF FRACTIONAL REPEATABILITY STANDARD DEVIATIONS OF SEVERAL LOAD-CARRYING CAPACITY TEST METHODS

	Fractional Repeatability Standard Deviation							
	Standard Ryder Test Gears (AMS 6260 Steel)		SwRI Design H. T. Test Gears				Design X H. T. Test Gears (Nitralloy N Steel)	
			M-50 Steel		Nitralloy N Steel			
Oil Code	165°F	400°F	165°F	400°F	165°F	400°F	165°F	400°F
Reference "B"	0.109	0.143	-	-	-	-	-	-
GTO-313	0.136	0.092	-	-	-	0.403	-	0.091
GTO-770	0.065	0.285	-	-	0.002	0.082	-	-
GTO-790	0.072	0.452	-	0.094	-	-	-	-
GTO-794, 803	0.093	0.520	-	-	-	0.255	-	0.162
GTO-855	0.077	0.237	-	0.101	0.016	0.165	-	0.063
GTO-861, 885-1, 915	0.082	0.054	0.042	-	0.126	0.277	0.044	0.069
GTO-882, 939	0.090	0.540	-	-	0.019	0.212	-	0.081
LRO-8, 11	0.044	0.057	-	-	0.123	0.158	-	0.078
LRO-13	0.066	0.242	-	-	0.007	0.091	-	0.043

fractional repeatability standard deviation is apparent for the 400°F load-carrying capacity test using the standard Ryder test gears and the SwRI design Nitralloy N steel test gears. The overall fractional repeatability standard deviation of the 400°F load-carrying capacity test using the WADD high-temperature gear machine, considering all types of test gears, is of the order of 0.15. There is no comparative information on 400°F load-carrying capacity test using the standard Ryder gear machine, because it has not been possible to operate the standard machine reliably at 400°F.

The data obtained to date on test reproducibility are not extensive. However, from the data presented in Tables 4, 5, 6 and 7, it appears that the reproducibility of tests with the WADD high-temperature gear machine was comparable to that of tests with the standard Ryder gear machine at 165°F test temperature.

2. Scuff-Limited Load

The average scuff-limited loads of ten lubricant types, determined in the WADD high-temperature gear machine at two lubricant temperatures, using four test gear types, have been summarized in Table 8. Before examining the results in detail, it may be of interest to reflect on the general trends. On the whole, the different lubricants tend to respond differently to changes in test gear type and lubricant temperature. First, it will be observed that, with standard Ryder test gears, all test lubricants suffered a definite reduction in scuff-limited load, though in varying amounts, when the lubricant temperature was increased from 165 to 400°F. On the other hand, with M-50 steel test gears, the scuff-limited load of most of the lubricants tested was practically not affected by the same increase in lubricant temperature. Another noteworthy trend is that the scuff-limited load of most of the lubricants tested was considerably enhanced by the use of the high-temperature test gears. However, with some lubricants, no appreciable benefit was derived from the use of one or the other of the three types of high-temperature test gears.

Figure 15 shows the relation between the scuff-limited loads obtained with standard Ryder test gears at 165°F and 400°F oil temperatures. This figure is derived from the data presented in Table 8. It would seem that if a correlation existed between the results from the two temperature conditions, the correlation curve must pass through the origin. On this basis, a straight line passing through the origin has been drawn. It is seen that the scatter of data points about the line is quite considerable. However, taking the data as a whole, there is no question that a definite reduction was obtained with all of the lubricants tested, when the lubricant temperature

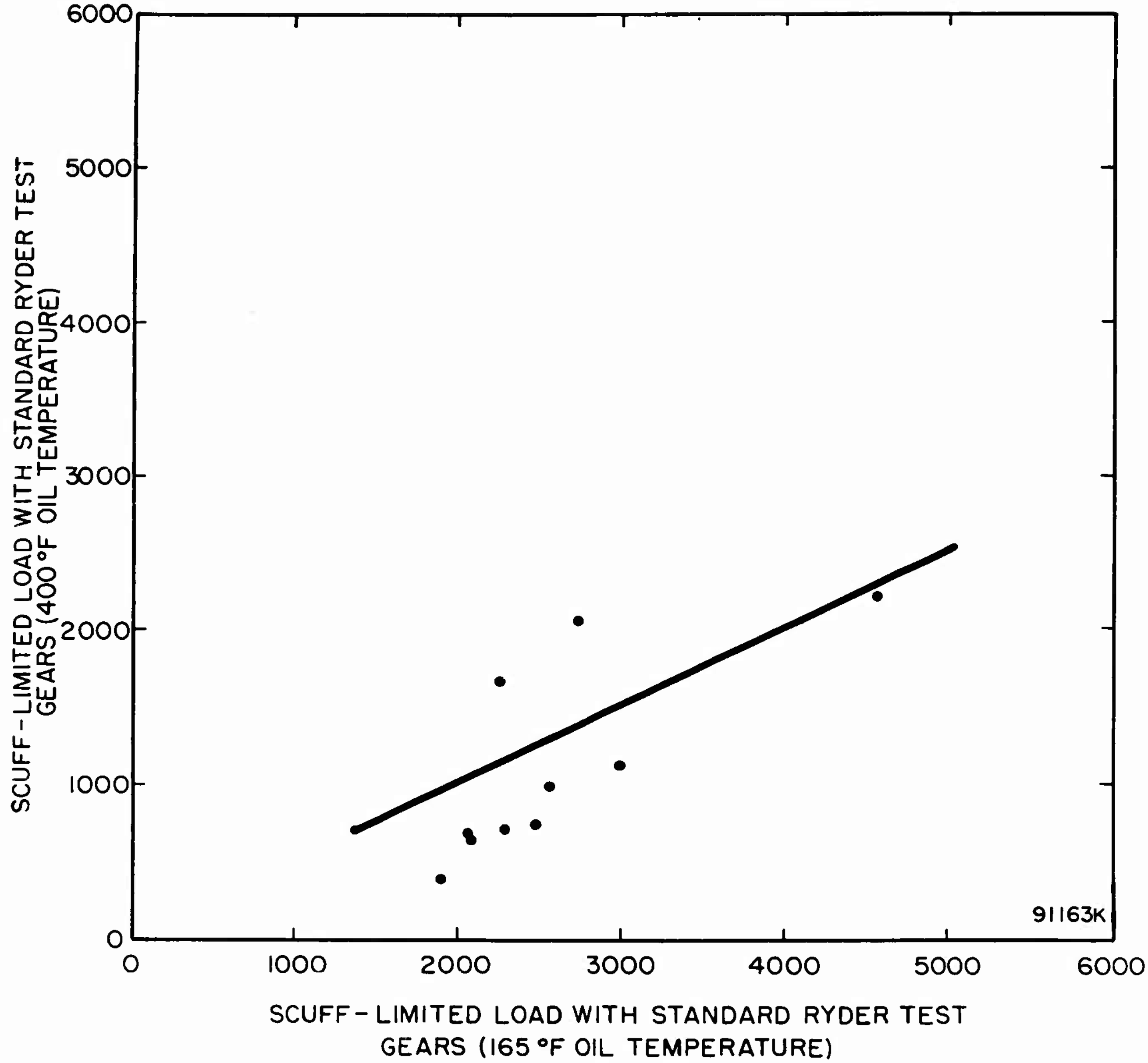


FIGURE 15. RELATION BETWEEN SCUFF-LIMITED LOADS OBTAINED WITH STANDARD RYDER TEST GEARS AT 165°F AND 400°F OIL TEMPERATURES

was increased from 165 to 400°F; the reduction being of the order of 20 to 80 percent depending upon the lubricants.

The scuff-limited loads obtained with M-50 steel test gears (SwRI design) at 165°F and 400°F oil temperatures are plotted in Figure 16 against those obtained with standard Ryder test gears at 165°F oil temperature. Note that within the range of scatter of the data points, there was no organized difference between the results obtained at the two oil temperatures. Generally speaking, the use of M-50 steel test gears increased the scuff-limited load of the lubricants over that obtained with the standard Ryder test gears. At either oil temperature, this increase was of the order of 10 to 25 percent depending on the lubricants.

The relation between the results obtained with Nitralloy N steel test gears at 400°F oil temperature and those obtained with standard Ryder test gears at 165°F is shown in Figure 17. Weighted straight lines passing through the origin are drawn for both the SwRI design and Design X. Note that, within the range of scatter, test gears of Design X gave higher scuff-limited load than test gears of SwRI design. However, the scatter was so large that no quantitatively valid conclusion can be drawn.

Figure 18 shows the relation between the results obtained with the Nitralloy N steel test gears at 400°F oil temperature, with the results obtained with standard Ryder test gears at the same oil temperature. Note that the scuff-limited load was increased when Nitralloy N steel test gears were used in place of standard Ryder test gears. This increase in scuff-limited load was of similar order of magnitude as that observed with M-50 steel test gears; but again large variations existed depending on the lubricants

Taking the data as a whole, there is enough evidence to show that scuff-limited load was influenced by lubricant type, gear material and design, and operating conditions, in a complex and essentially unpredictable manner. From the theoretical standpoint, there is indeed no reason to believe that lubricants of different types, composed of load-carrying additives of different types, will not exhibit different load-carrying characteristics in combination with different gear materials under different operating conditions. This situation has been reported in the literature by several investigators.[11.02, 11.03, 11.04, 11.05] It appears that this situation should be duly recognized in lubricant evaluation studies. It does not appear that tests conducted on a lubricant with one gear material under certain operating conditions could provide a realistic measure of the load-carrying capacity of the same lubricant when used in conjunction with a different gear material under different operating conditions.

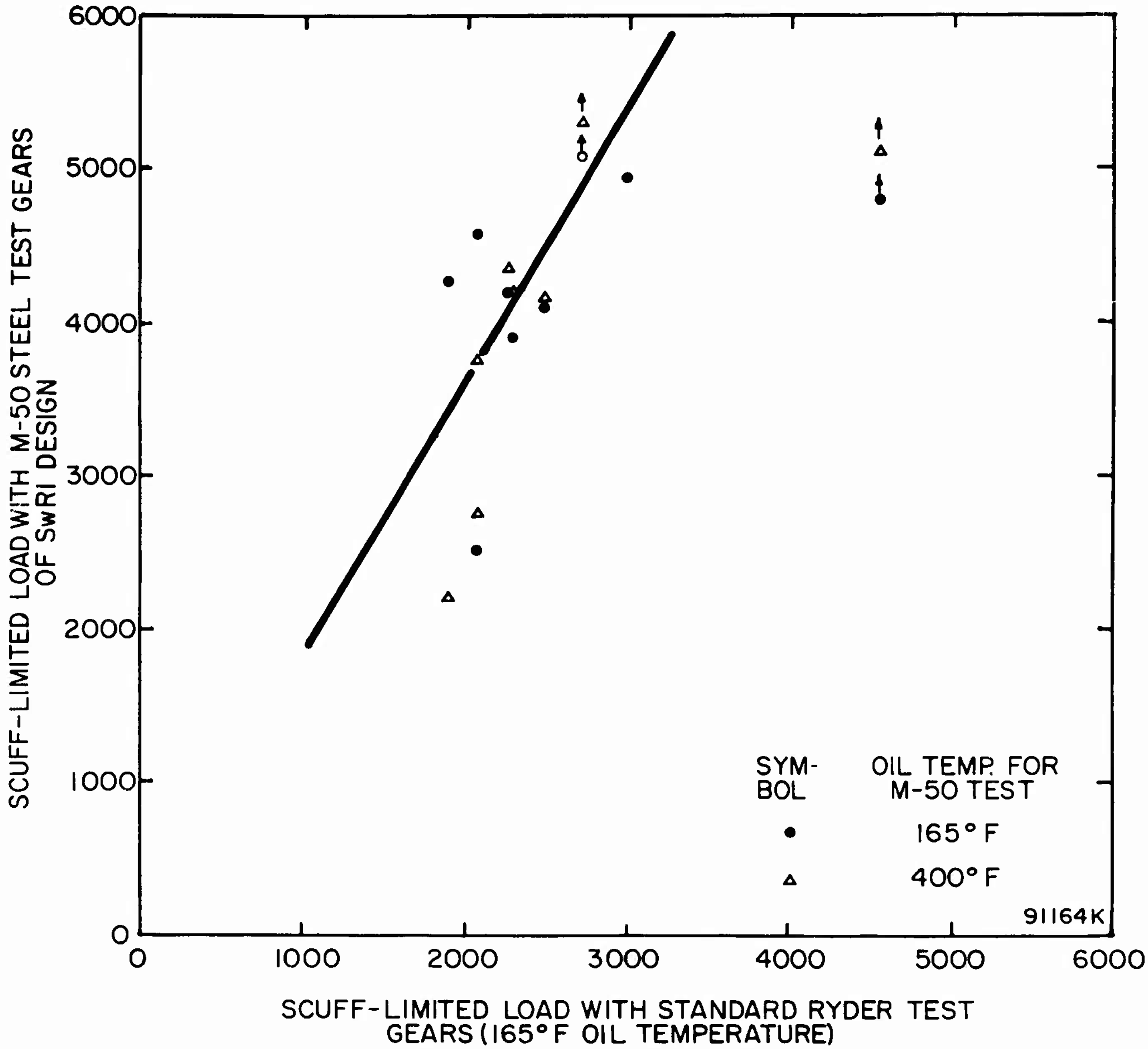


FIGURE 16. RELATION BETWEEN SCUFF-LIMITED LOADS OBTAINED WITH M-50 STEEL TEST GEARS AT 165°F AND 400°F OIL TEMPERATURES WITH THAT OBTAINED WITH STANDARD RYDER TEST GEARS AT 165°F OIL TEMPERATURE

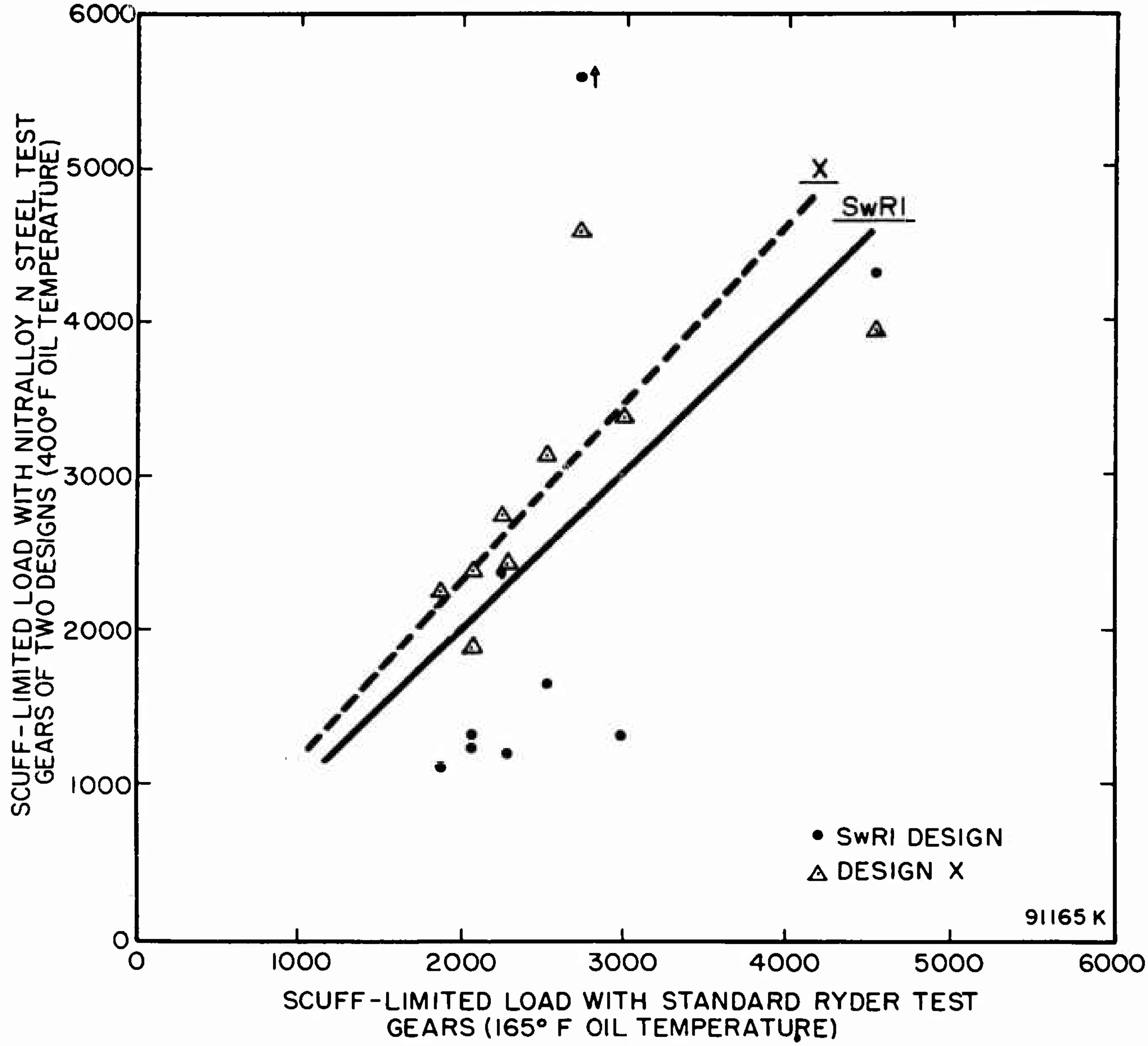


FIGURE 17. RELATION BETWEEN SCUFF-LIMITED LOADS OBTAINED WITH NITRALLOY N STEEL TEST GEARS OF TWO DESIGNS AT 400° F OIL TEMPERATURE WITH THAT OBTAINED WITH STANDARD RYDER TEST GEARS AT 165° F OIL TEMPERATURE

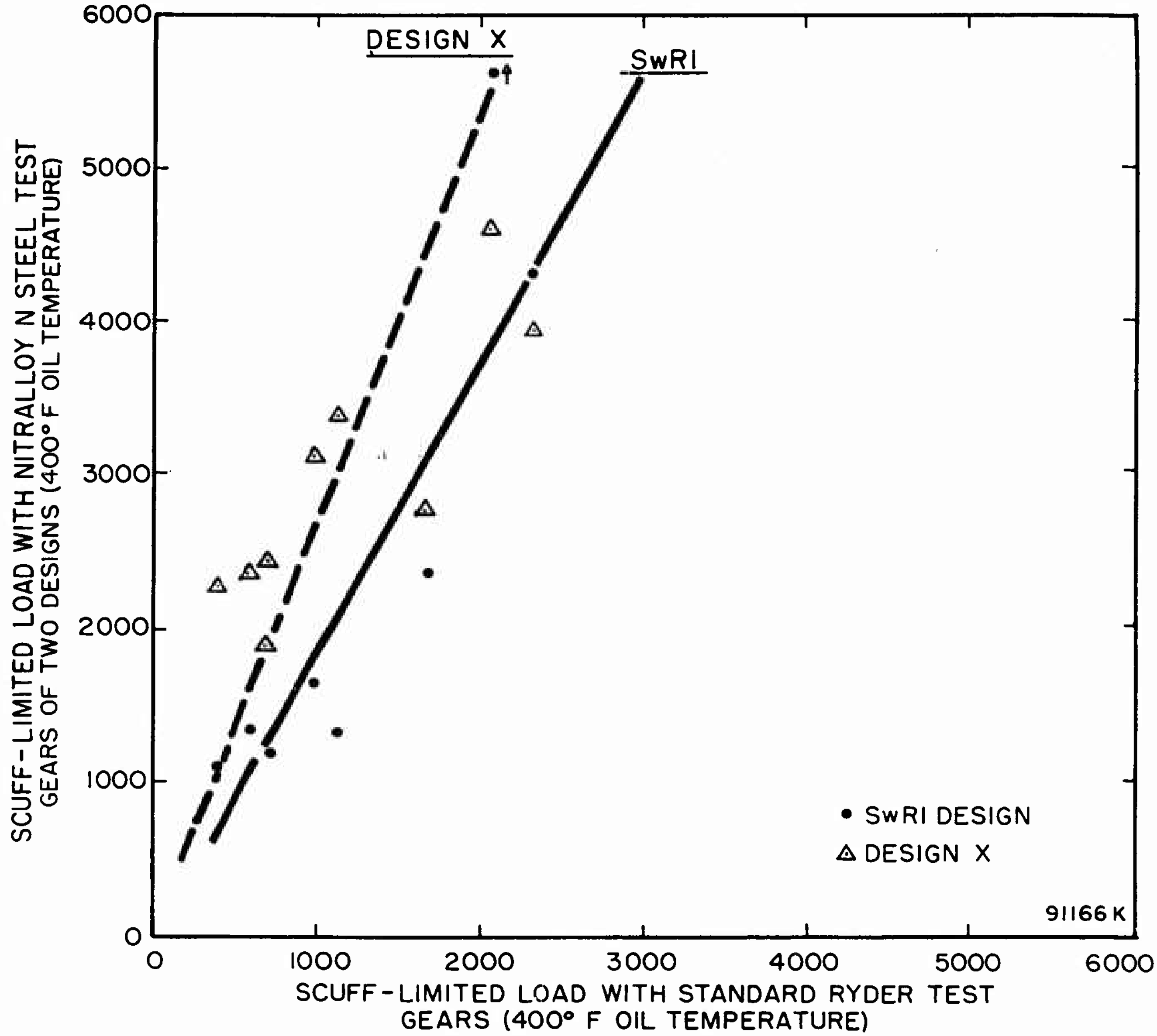


FIGURE 18. RELATION BETWEEN SCUFF-LIMITED LOADS OBTAINED WITH NITRALLOY N STEEL TEST GEARS OF TWO DESIGNS AT 400°F OIL TEMPERATURE WITH THAT OBTAINED WITH STANDARD RYDER TEST GEARS AT 400°F OIL TEMPERATURE

Effect of Test Oil Flow Rate. The effect of test oil flow rate on the scuff-limited load of GTO-915 obtained with Nitralloy N steel test gears at 400°F oil temperature is shown in Table 11. From these results, it appears that an increase in test oil flow rate from 270 to 1000 ml/min had little effect on the scuff-limited load obtained. These results confirm the data obtained earlier[11.04] on two other synthetic lubricants at 165°F, using a standard Ryder gear machine and standard Ryder test gears. It should be recalled that, in all these experiments, the lubricant was introduced on the exit side of the gear mesh. Since the lubricant tends to be thrown out, due to gear rotation, when the gears come into mesh, the effect of flow rate would not be expected to be large.

Effect of Test Oil Deterioration. For those tests reported in Table 11 that were conducted at 1000 ml/min flow rate, the test oil was not changed until the neutralization number was increased by approximately 1.0 mg KOH/g. These results in Table 11 have been rearranged in Table 12 to show the sequence by which the tests were run. It will be seen that no organized trend can be noted as to the effect of oil deterioration on scuff-limited load.

The effect of oil deterioration on scuff-limited load is, in general, hard to predict. With some lubricants, an increase in scuff-limited load with deterioration has been reported.[11.04] There appears to be no doubt that the variation is dependent upon lubricant type, and possibly gear material and other factors.

3. Test Gear Hardness

Hardness determinations were made on new and used standard Ryder test gears (AMS 6260 steel) and Nitralloy N steel test gears, using a Rockwell superficial hardness tester. All of the used gears were those taken after the 400°F load-carrying capacity tests. The determinations were made on tooth side and/or face of each gear at positions 120° apart. However, measurements were not made on the tooth face of the new gears since to do so would damage the tooth face surface.

The data on the standard Ryder test gears are shown in Table 13. In this table, several hardness determinations previously made[0.85] have been included, but the unit of measurement has been converted from the Rockwell C scale of the original readings to the Rockwell 15 N scale equivalent. The hardness data indicate that the difference in hardness between the side and face of the tooth was small.

TABLE 11. EFFECT OF TEST OIL FLOW RATE ON SCUFF-LIMITED LOAD

Test Oil Flow Rate, ml/min	SwRI Design Nitralloy N Test Gears: Scuff-Limited Load, lb/in.		SwRI Design: Test Oil at End of Test: Vis. at 100°F		SwRI Design: Neut. No.		Design X Nitralloy N Test Gears: Scuff-Limited Load, lb/in.		Design X: Test Oil at End of Test: Vis. at 100°F		Design X: Neut. No.	
	A	B	A	B	A	B	A	B	A	B	A	B
270	1450	1150	-	-	-	-	2230	2330	-	-	-	-
	950	1090	-	-	-	-	2230	1950	-	-	-	-
	710	1670	16.8	16.6	0.40	0.50	2380	2430	17.28	16.77	0.56	0.36
	740	1150	16.6	16.7	0.37	0.21						
	1110						2260					
1000	890	700	17.0	17.0	0.44	0.94	2220	2200	16.8	17.1	0.30	0.52
	1750	550	16.3	16.4	0.14	0.28	2590	2460	17.5	18.2	0.68	0.97
	570	1700	16.7	16.4	0.97	0.06	2620	1680	16.2	16.2	0.09	0.08
	1030						2300					

All tests were run with Nitralloy N steel test gears and WADD high-temperature gear machine No. 1. GTO-915 at 400°F supply temperature was used.

TABLE 12. EFFECT OF TEST OIL DETERIORATION ON SCUFF-LIMITED LOAD

Test Sequence	Test Gears	Gear Side	Scuff-Limited Load, lb/in.	Test Oil at Start of Test: Vis. at 100°F	Test Oil at Start of Test: Neut. No.	Test Oil at End of Test: Vis. at 100°F	Test Oil at End of Test: Neut. No.
1	Design X	A	2220	16.0[a]	0.04[a]	16.8	0.30
		B	2220	16.8	0.30	17.1	0.52
2	Design X	A	2590	17.1	0.52	17.5	0.68
		B	2460	17.5	0.68	18.2	0.97
3	Design X	A	2620	16.0[a]	0.04[a]	16.2	0.09
		B	1680	16.2	0.09	16.2	0.08
4	SwRI design	A	890	16.2	0.08	17.0	0.44
		B	700	17.0	0.44	17.0	0.94
5	SwRI design	A	1750	16.0[a]	0.04[a]	16.3	0.14
		B	550	16.3	0.14	16.4	0.28
6	SwRI design	A	570	16.4	0.28	16.7	0.97
		B	1700	16.0[a]	0.04[a]	16.4	0.06

All tests were run with Nitralloy N steel test gears and WADD high-temperature gear machine No. 1. GTO-915 was used, at 400°F supply temperature and 1000 ml/min flow rate. The test oil sump capacity was 2 gallons.

(a)New test oil was introduced at the start of the test.

TABLE 13. COMPARISON OF TOOTH SIDE AND FACE HARDNESS OF NEW AND USED STANDARD RYDER TEST GEARS

Gear No.	Hardness, Rockwell 15 N Scale							
	Position, Tooth Side				Position, Tooth Face (a)			
	1	2	3	Avg.	1	2	3	Avg.
New Gears								
K-271 (b)	91.2	90.7	91.0	91.0	-	-	-	-
J-780 (b)	91.0	91.0	91.0	91.0	-	-	-	-
J-887 (b)	90.7	90.7	90.5	90.6	-	-	-	-
L-266	91.2	92.0	89.0	90.7	-	-	-	-
L-422	90.3	89.9	92.0	90.7	-	-	-	-
L-430	90.7	90.5	90.0	90.4	-	-	-	-
Gears After 400°F Scuff Tests (c)								
H-554	88.2	88.5	88.8	88.5	90.2	88.7	89.0	89.3
G-190	88.0	84.5	85.0	85.8	89.2	89.7	89.1	89.3
H-821	88.5	87.5	88.0	88.0	89.3	88.9	89.9	89.4
J-24	88.5	88.5	89.2	88.7	90.5	91.0	90.4	90.6
K-64	89.0	89.0	88.5	88.8	88.9	90.5	90.1	89.8
K-909	89.1	89.2	86.8	88.4	90.8	90.0	90.2	90.3
K-260	89.2	89.2	89.0	89.1	90.3	90.7	90.0	90.3
K-679	86.2	89.0	88.5	87.9	89.3	90.8	88.7	89.6

(a) The positions 1, 2, 3 on the tooth face do not necessarily correspond to the same ones taken on the tooth side.

(b) These values were converted from Rockwell C hardness tests.

(c) The hardness determinations on the tooth side after 400°F scuff tests were converted from Rockwell C scale hardness tests.

Hardness data on new and used Nitralloy N steel test gears, of both SwRI design and Design X, are presented in Table 14. Again, no appreciable difference was noted between the hardness of the tooth face and that of the tooth side.

The average values of the hardness readings for the standard Ryder test gears and the Nitralloy N steel test gears are shown in Table 15, together with additional data previously reported.(0, 85) It can be seen that there was no change in hardness for the Nitralloy N steel and M-50 steel test gears after they had been run in 400°F load-carrying capacity tests. On the other hand, the standard Ryder test gears showed a definite reduction in hardness after tests at elevated temperatures.

4. Gear-Blank Temperature Measurements

For preliminary experimentation with infrared radiometry as a means to measure the gear-blank temperature in a gear machine in operation, a used and slightly scuffed M-50 steel narrow test gear was plated with a black chromium ring as shown in Figure 9. This gear was installed, along with a used M-50 steel wide test gear, in a WADD high-temperature gear machine. The radiometer was focused on the black chromium ring through one of the inspection holes in the gear case end cover as shown in Figure 19. The gear case was further fitted with a compression thermocouple which could be pressed against the narrow test gear (in the vicinity of the point of focus of the radiometer) when the machine was stopped. This thermocouple was used to serve as a check against the radiometer.

Figure 20 shows the results obtained in this preliminary experiment, in which a MIL-L-9236 type lubricant was used. The gear machine was first brought to the operation conditions of the 400°F load-carrying capacity test, with the lubricant circulating but the machine standing still. After thermal equilibrium was attained, the gear-blank temperature was found to be 400°F as indicated by both the radiometer and the compression thermocouple. The thermocouple was then retracted, the machine was operated at 10,000 rpm, and load was applied to the test gears. The initial load oil pressure used was 15 psig, giving a gear tooth load of 690 lb/in. After the load was applied, the gear-blank temperature was found to rise rapidly, reaching a value of 430°F at the end of a 10-minute run. When the load was removed and the machine stopped, the gear-blank temperature dropped rapidly, returning to 400°F at the end of a 10-minute shutdown. The test was continued at successively increasing loads, in otherwise identical manner, until the load oil pressure reached 70 psig (corresponding to 3220 lb/in. tooth load). Note that as the load was increased, the gear-blank temperature rose accordingly. Further, at higher loads, the gear-blank

TABLE 14. COMPARISON OF TOOTH SIDE AND FACE HARDNESS OF NEW AND USED NITRALLOY N STEEL TEST GEARS

	Hardness, Rockwell 15 N Scale							
	Position, Tooth Side				Position, Tooth Face			
Gear No.	1	2	3	Avg.	1	2	3	Avg.
New SwRI Design Gears								
8	90.1	91.6	91.3	91.0	-	-	-	-
17	90.8	90.1	90.7	90.5	-	-	-	-
21	90.2	90.1	90.2	90.2	-	-	-	-
22	91.2	91.3	91.3	91.3	-	-	-	-
35	91.4	90.7	90.6	90.0	-	-	-	-
37	91.1	91.2	90.1	90.8	-	-	-	-
SwRI Design Gears After 400°F Scuff Tests								
13	90.5	90.4	90.1	90.3	92.8	93.1	93.1	93.0
25	91.6	91.3	91.6	91.5	90.8	91.0	92.2	91.3
36	91.0	90.8	91.6	91.1	90.8	91.2	90.8	90.9
9	91.2	91.8	91.0	91.2	91.5	91.2	91.8	91.5
30	91.3	90.1	91.5	90.9	90.0	90.1	91.5	90.2
29	91.0	91.8	91.6	91.5	91.1	91.0	91.5	91.2
New Design X Gears								
5070	92.0	92.3	92.5	92.3	-	-	-	-
5075	91.8	92.4	91.8	92.0	-	-	-	-
5086	91.7	91.9	92.0	91.9	-	-	-	-
5106	91.7	92.2	92.4	92.1	-	-	-	-
5108	92.0	92.3	92.6	92.3	-	-	-	-
5105	91.7	92.3	91.8	91.9	-	-	-	
Design X Gears After 400°F Scuff Tests								
5070	92.7	93.0	93.8	93.2	-	-	-	-
5075	93.1	93.5	93.8	93.4	-	-	-	-
5086	93.5	93.3	93.6	93.5	-	-	-	-
5105	93.1	93.1	92.3	92.8	-	-	-	-
5106	92.9	93.6	93.9	93.4	-	-	-	-
5108	94.1	94.2	94.2	94.1	-	-	-	-

TABLE 15. COMPARISON OF HARDNESS OF SEVERAL GEAR TYPES

	Hardness, Rockwell 15 N Scale			
	Standard Ryder Test Gears (AMS 6260 Steel)	M-50 Steel Test Gears[a] (SwRI Design)	Nitralloy N Steel Test Gears	
			SwRI Design	Design X
Specification Requirement	90-92	90-92	90-92	92-94
New Gears, Measured	89-92	91-92	90-92	92-94
After 165°F Scuff Tests, Measured	89-90[a]	-	-	-
After 400°F Scuff Tests, Measured	85-89	91-92	90-93	92-94

(a)Data derived from Reference 0.85.

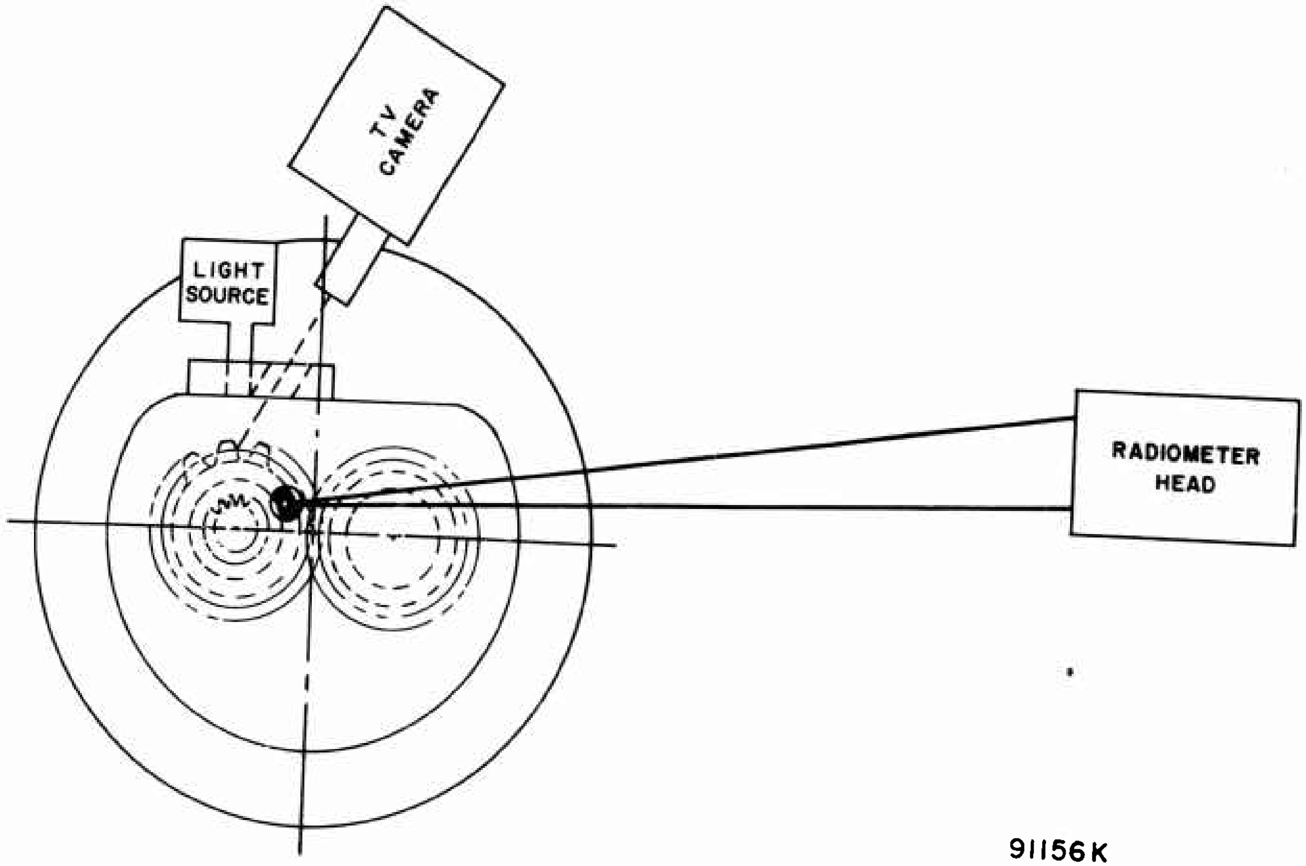


FIGURE 19. POSITION OF RADIOMETER, TELEVISION CAMERA AND LIGHT SOURCE

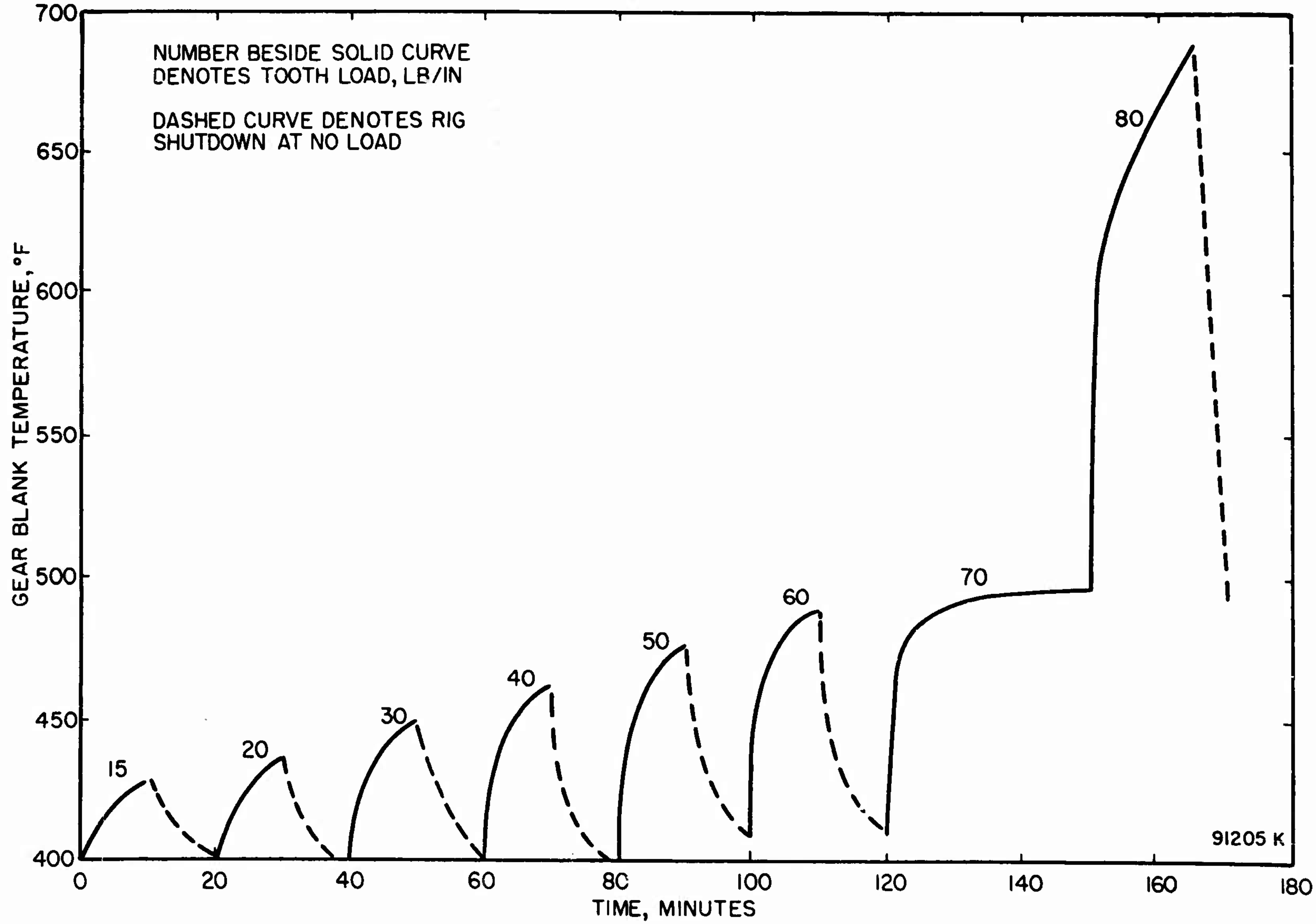


FIGURE 20. GEAR-BLANK TEMPERATURES MEASURED DURING STEP LOADING

temperature did not return to 400°F after a 10-minute shutdown, indicating that there was not enough time for thermal equilibrium. The machine was allowed to run at 70 psig load oil pressure for 30 minutes, and the gear-blank temperature was found to level off at 495°F in about 20 minutes. After this 30-minute period, the load oil pressure was further increased to 80 psig (or 3680 lb/in. tooth load) without stopping the machine. An increase in scuff occurred at this load, and the gear-blank temperature reached 690°F after 15 minutes of operation, at which time the test was terminated.

Following the preliminary experiment, gear-blank temperature measurements were made during approximately 160 tests in the load-carrying capacity test program discussed in the preceding sections. A recorder was used in conjunction with the radiometer, and traces were obtained similar to that shown in Figure 20. For each of the tests, plots were prepared for the gear-blank temperature attained at the end of each 10-minute loading period, versus the load oil pressure. Figure 21 shows a typical example of such a plot, composed of results obtained in five 400°F load-carrying capacity tests on GTO-313 lubricant, using Nitralloy N steel test gears of Design X. With other lubricants, gear types and operating conditions, plots of similar general description, though of different numerical values, were obtained.

In general, it was observed that the gear-blank temperatures rose steadily as the load was progressively increased, even at low loads when no appreciable scuffing could be detected. This temperature rise could only have been due to the energy dissipated by shearing of the oil film on the contacting teeth, and the energy dissipated by hysteresis due to bending of the contacting teeth as well as elastic deformation of the contacting surfaces. The gear-blank temperature was found to increase sharply after scuffing occurred, due no doubt to the energy dissipated in the scuffing process. It was further noticed that, in general, the scatter of the gear-blank temperature readings before the onset of scuffing was not nearly as large as that obtained after scuffing occurred. This could be due partly to the random nature of the scuffing process, and partly to the lack of thermal equilibrium at high loads in the standard 10-minute step-load period.

In any discussion of gear temperature measurements, it is difficult to refrain from referring to the "flash temperature theory" first introduced by Blok[11.06], and later refined by Kelley[11.07] and Blok[11.08]. It should be emphasized that the temperature measurements reported here were taken in the course of a regular test program, which was not specifically designed to explore a basic concept. It is not the intent to dwell further on the subject of the flash temperature theory, except to note that the technique that has been developed here may well be utilized in such a study.

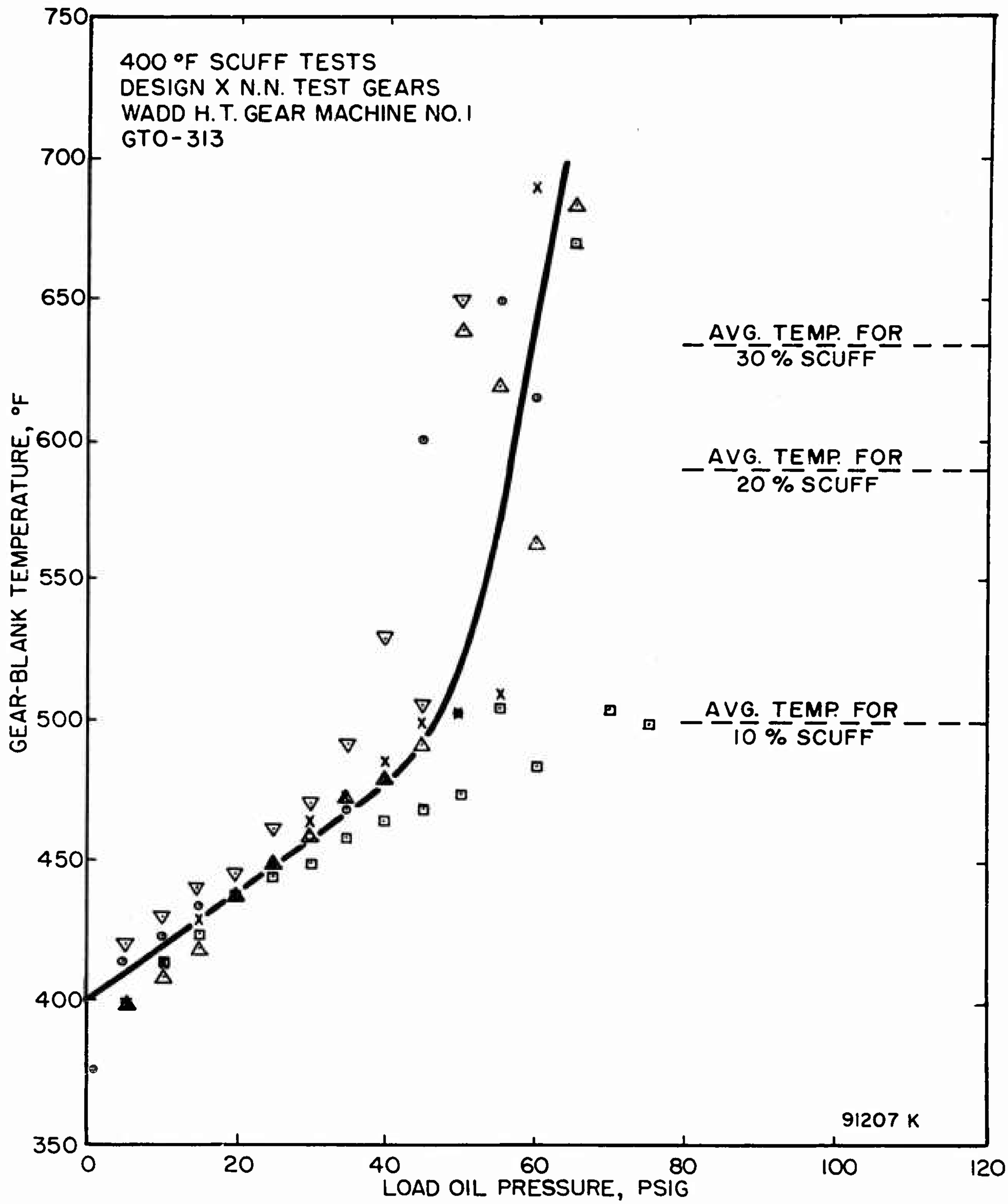


FIGURE 21. GEAR-BLANK TEMPERATURES FOR GTO-313

5. 400°F Gear Load-Carrying Capacity with Induction Heating

Load-carrying capacity tests were conducted with the test gear blank temperature and test oil temperature controlled at 400°F. The test conditions were as follows:

Test gear speed, rpm	10,000 ± 100
Test oil flow rate, ml/min (exit lubrication)	270 ± 5
Gear blank temperature, °F	400 ± 15
Test oil-in temperature, °F	400 ± 5
Support oil-in temperature, °F	165 ± 5

The test gear blank temperature was maintained at 400°F by means of induction heating, which was controlled by use of the infrared radiometer in conjunction with a strip chart recorder-controller system described in a preceding section. The test oil temperature was maintained at 400°F by using the 400°F test oil system. The support oil temperature was maintained at 165°F by using the standard 165°F support oil system.

The operating procedure for induction heating and temperature control of the test gears is very simple in that with the induction heater and radiometer in operation, the operator needs only to set the recorder-controller at the desired gear blank temperature. The test gears are then automatically heated and the temperature controlled and recorded within a matter of minutes, requiring no further attention from the operator other than normal observations of the control system.

Scuff-Limited Load with Controlled Gear Temperature. The results of the 400°F gear load-carrying capacity determinations using the induction heating method for heating the test gears are shown in Table 16. The results obtained using the standard 400°F method are also shown for the purpose of comparison. As can be seen, the scuff-limited load values obtained for the lubricants shown are somewhat higher in the tests using induction heating than in the tests where induction heating was not used. This was expected since the induction heating method controls the test gear blank temperature at a constant 400°F; whereas, in the latter case, the test gear temperature is not controlled directly, but is allowed to seek its thermal equilibrium value which has been found to be higher than 400°F at gear tooth loads at which limiting scuff is obtained.

TABLE 16. COMPARISON OF 400°F SCUFF-LIMITED LOAD RESULTS OBTAINED WITH THE INDUCTION HEATING METHOD AND THE STANDARD 400°F METHOD USING SwRI DESIGN NITRALLOY N TEST GEARS

	400°F Induction Heating Method[a]			Standard 400°F Method [b]		
	Average Gear Temp.	Scuff-Limited Load, lb/in.		Average Gear Temp.	Scuff-Limited Load, lb/in.	
Oil Code	at 22.5% Scuff	A	B	at 22.5% Scuff	A	B
GTO-313	400	2060	2540	480	2340	4310
	400	2620	2380	480	3080	2840
				480	1560	1520
				480	1270	1970
		2400			2360	
GTO-770	400	5990[c]	6230[c]	485	4580	4710
				485	3810	4220
				485	3940	4670
		6110			4320	
GTO-855	400	2910	2490	430	1240	1080
	400	3320	3220	430	790	1030
				430	1330	1430
				430	1360	1220
		2990			1190	
GTO-915, 0-60-23	400	1110	1620	420	1450	1150
	400	2100	1450	420	950	1090
				420	710	1670
				420	740	1150
		1570			1110	
GTO-939	400	1840	1570	400	1340	1670
	400	1470	1600	400	1540	1220
		1620			1440	
LRO-11	400	1830	1710	420	1280	1310
	400	1400	1640	420	1520	1400
				420	840	1500
				420	1250	1510
		1640			1330	
LRO-13	400	1780	1990	-	1620	1720
	400	2160	2460	-	1430	1640
				-	1760	1880
				-	1710	1410
		2100			1650	

(a) Tests were made using WADD high-temperature gear machine No. 2.
(b) Tests were made using WADD high-temperature gear machine No. 1.
(c) Values obtained by extrapolation. Test was terminated at 5600 lb/in. tooth load.

In earlier considerations of high-temperature gear lubrication research(0.85), it was emphasized that the temperature of the gear teeth and the temperature of the lubricant should be accurately and independently defined and controlled. Since instrumentation capabilities at that time were such that accurate and independent variations of gear and lubricant temperature could not be readily obtained, it was decided to forego this experimental flexibility and vary the test oil and support oil temperatures together, allowing the test gear temperature to seek its thermal equilibrium value during test. Using this procedure, the equilibrium gear blank temperature during test was expected to rise above that of the test oil and support oil, especially at heavy tooth loads. However, the amount of this temperature rise, or what this temperature rise would mean in terms of load-carrying capacity, remained to be determined.

As discussed earlier in this report, gear blank temperature measurements were made during approximately 160 tests in the standard 400°F load-carrying capacity program. In general, referring back to Figure 21, it was observed that the gear blank temperature increased steadily as the load was progressively increased, and a sharp increase was noted in most cases when scu..ng occurred. The amount of increase in gear blank temperature was found to vary with lubricant type, test gear material, test gear design, and the manner in which the lubricant was supplied. With some high load-carrying capacity lubricants at gear tooth loads which produced limiting scuff, the gear blank temperature was found to be as much as 200°F above the controlled test oil and support oil temperature.

From the work conducted to date, it has been found that, with an increase in lubricant temperature, the load-carrying capacity generally tends to decrease. From this, it is not difficult to understand the approximately 1800 lb/in difference in tooth load, shown in Table 16 for GTO-770, since with induction heating, the gear blank temperature was maintained at 400°F; whereas, the gear blank temperature rose to 485°F during the standard 400°F test. From these results (Table 16), it can therefore be seen that equivalent evaluations cannot be reliably made of different types of lubricants under conditions of high operating temperatures without control of both the lubricant and gear blank temperature.

D. Investigations on Gear Tooth Fatigue

Due to the length of the fatigue tests only 13 determinations were obtained during the contract period. Two different oils, five test procedures, and two different gear tooth forms were used in these tests. Since the primary objective of the present fatigue studies is the development of a

high-temperature fatigue procedure, no special emphasis has been placed on repeatability other than as an indication as to the effect of the variables in the test procedure.

1. Development of 400°F Fatigue Test Procedure

Effort was directed toward the development of a 400°F fatigue test procedure using Nitralloy N steel test gears of SwRI design. The test procedures explored are shown in Table 17. The test conditions varied in the studies were speed, means of lubrication and tooth load. In Test Procedures A and B, the test gears were lubricated by directing the test oil through two identical jets, one at the meshing and the other at the unmeshing sides of the gear teeth. In Test Procedures C, D and E a single jet was used to direct the test oil to the meshing side of the gear teeth.

The gear tooth load was obtained using the scuff-limited load procedure of loading; the load oil pressure was increased in steps of 5 psi (230 lb/in. tooth load) of 10-minute duration each until the specified tooth load was obtained. After each 10-minute run, the gear machine was stopped and the narrow test gear examined for scuff by closed-circuit television. The fatigue test was then commenced at the specified tooth load. During the fatigue test, the machine was stopped every two hours for the purpose of examining the narrow test gear for scuff and pits. Also, a sample of the test oil was collected at that time. The fatigue characteristics of the gear-lubricant combination were determined by the time required to produce "B" pits on three nonconsecutive gear teeth.[11.09] "B" pits are defined as pits of such size as to be readily identifiable without the aid of magnification.

The preliminary investigations were made on test gears which had previously been used in scuff-limited load tests. The gears had been run for a total of about 16 hours with scuff averages of between three and seven percent. Test Procedures A and B, which are identical with exception of gear speed, were investigated using these gears. In both cases, excessive scuffing was encountered at moderate tooth loads of 1400 and 2500 lb/in., respectively, during the step loading phase, indicating the necessity for a reduction in test severity level. Since further reduction in speed was not desirable, attention was then directed toward the lubrication system. It was found that less scuff was produced during the step loading phase by directing the test oil at the meshing sides of the gear teeth through a single jet, rather than by splitting the oil flow between the meshing and unmeshing sides of the gear teeth via two jets. However, the mean scuff obtained was still in excess of the scuff level considered feasible for fatigue testing. This necessitated a reduction of the tooth load from 4000 lb/in. to approximately 2000 lb/in.

TABLE 17. SUMMARY OF GEAR FATIGUE TEST PROCEDURES STUDIED

Operating Conditions	Test Procedures				
	A	B	C	D	E
Test gear speed, rpm	10,000 ± 100	5,000 ± 50	5,000 ± 50	5,000 ± 50	5,000 ± 50
Test oil flow rate, ml/min[a]	1,300 ± 25	1,300 ± 25	1,300 ± 25	1,300 ± 25	1,300 ± 25
Test oil-in temperature, °F	400 ± 5	400 ± 5	400 ± 5	400 ± 5	400 ± 5
Support oil-in temperature, °F					
High-temperature section	400 ± 5	400 ± 5	400 ± 5	400 ± 5	400 ± 5
Low-temperature section	165 ± 5	165 ± 5	165 ± 5	165 ± 5	165 ± 5
Tooth load, lb/in.[b]	4,000	4,000	2,000	1,800	1,500

(a)Two identical jets were used to deliver the test oil, one to the meshing and the other to the unmeshing sides of the gear teeth in Procedures A and B. A single jet was used to direct the test oil to the meshing sides of the gear teeth, in Procedures C, D and E.

(b)Gear tooth loads were obtained by increasing the load oil pressure in steps of 5 psi of 10 minutes duration each.

As a result of these studies, Test Procedures C and D were decided upon and were used in the early lubricant fatigue determinations. In the later tests, Test Procedure D was further modified with respect to gear tooth load. This modified procedure is referred to as Test Procedure E in Table 17. In addition, test gears with a tip-relieved tooth form of 0.0015 in. were used in these procedures.

2. Gear Tooth Fatigue

The major portion of the gear fatigue work was centered around Test Procedures C and D, which are identical with the exception of the gear tooth load. The data obtained are presented and discussed with respect to the effect of gear tooth load and gear tooth scuff on the fatigue life of the gear teeth.

A summary of the results obtained in the fatigue investigations is presented in Table 18. A total of six tests were conducted on GTO-915 and GTO-950 using Test Procedure C and standard tooth form gears. Of these tests, it can be seen that only Test 3862B was not in close agreement, and Test 3860B was not considered valid since a tooth was broken before any pitting had occurred. The other four tests had an average time of 23 hours at the time of the first "B" pit and an average of 32 hours at the point of three nonconsecutive "B" pits. The standard deviation for the time to one "B" pit and three nonconsecutive "B" pits, for these four tests, were 9.4 and 13 hours respectively. The standard deviation divided by the mean for both of these values was 0.41. It will be noted that the repeatability of these tests was very comparable with that of the 165°F fatigue test previously reported.(11.09)

A careful study of the raw fatigue test data, gear machine maintenance log, and test gear hardness, was made for possible variations in test conditions. These studies did not reveal any condition that would account for the large deviation in time to three nonconsecutive "B" pits experienced in Test 3862B.

In the two tests on GTO-950 using Test Procedure D, Test 3862A only is considered valid since a tooth on the narrow test gear broke early in the endurance phase of Test 3861A. From the data shown in Table 18, it can be seen that a considerable increase in the time to three nonconsecutive "B" pits was experienced when the gear tooth load was decreased from 2000 lb/in. to 1800 lb/in. This seems to indicate that the fatigue life of this gear-lubricant combination experienced a sensitive break over a very narrow range of tooth load. On the other hand, it was found during the

TABLE 18. SUMMARY OF GEAR FATIGUE TESTS

Oil Code	Test Number	Test Procedure	Limiting Pitting, Hr. Cycles: 1 Tooth Hours	1 Tooth Cycles, 10^6	3 N-C Teeth Hours	3 N-C Teeth Cycles, 10^6	Mean Scuff All Teeth, %: Initial	1 Tooth Pitted	3 N-C Teeth Pitted
GTO-915	3858B	C	26	7.8	32	9.6	-	37	51
GTO-915	3859A	C	36	10.8	52	15.6	11	45	61
GTO-950[a]	3859B	C	20	6.0	28	8.4	15	43	54
GTO-950	3860A	C	10	3.0	16	4.8	16	27	30
GTO-950	3860B	C	>32[b]	>9.6	-	-	0	-	-
GTO-950	3862B	C	96	28.8	158	47.4	1	23	35
Mean[c]			37.4	11.2	57.0	17.1	10.7	35.0	46.2
Standard Deviation[c]			30.4	9.1	51.0	15.3	6.0	8.5	11.7
Standard Deviation/Mean[c]			0.81	2.4	0.89	2.7	0.56	0.24	0.25
GTO-950	3861A	D	16	4.8	>132[d]	>39.6	7	15	-
GTO-950	3862A	D	176	52.8	218	65.4	0	20	42
Mean			96.0	28.8	-	-	3.0	17.0	-
Standard Deviation			-	-	-	-	-	-	-
Standard Deviation/Mean			-	-	-	-	-	-	-
GTO-939	3863A	C	76	22.8	>250[e]	>75.0	5.2	15.9	>21.6[e]
GTO-939	3863B	C	16	4.8	54	15.0	5.9	27.3	31.6
Mean			46	13.8	-	-	5.5	21.6	-
Standard Deviation			30	9.0	-	-	0.5	5.7	-
Standard Deviation/Mean			0.65	1.8	-	-	0.09	0.26	-
0-60-23[a]	3864A-TR[f]	C	70	21.0	114	34.2	4.6	24.2	47.7
0-60-23	3864B-TR	E	136	40.8	212	63.6	0.4	15.0	15.4
0-60-23	3865A-TR[g]	E	>322	>96.6	-	-	0.0	-	-

All tests performed using WADD high-temperature gear machine No. 1.
(a) A different batch of GTO-915.
(b) Tooth chipped at 32 hours, test terminated (no "B" pits).
(c) Exclusive of Test 3860B.
(d) Tooth broke at 132 hours, test terminated (one "B" pit).
(e) Test terminated at 250 hours (one "B" pit).
(f) TR on test numbers denotes tip relieved gear.
(g) Test terminated at 322 hours. No "B" pits observed.

load-carrying capacity phase, that the load-carrying capacity standard deviation for this lubricant and gear combination was of the order of 300 lb/in. Thus the observed large effect of a change in tooth load of 200 lb/in. on the fatigue life is somewhat difficult to reconcile.

In Tests 3864A, 3864B and 3865A, a considerable increase in time to limiting pitting (three nonconsecutive "B" pits) was experienced with the combination of reduced tooth load and tip relieved tooth form.

3. Relationship of Gear Tooth Scuff and Gear Tooth Pitting

The possibility of a relationship between tooth scuffing and tooth surface fatigue was first suggested at the completion of Test 3860B. Referring to Figure 22, it can be seen that in this test there were no "B" pits at 32 hours endurance time and there was a correspondingly low amount of scuff. This suggested the possibility that there might be more than an incidental relationship between excessive scuff and pitting of the tooth surface. To further investigate this possibility, a comparison of gear tooth pitting with time and gear tooth pitting with the scuff was made as shown in Table 18. From these data it can be seen that the standard deviation of mean tooth scuff to both one and three nonconsecutive "B" pits was somewhat lower than that obtained for fatigue time.

In view of these findings, a review of the raw fatigue data was made. A comparison of the mean scuff of the nonpitted and pitted gear teeth, as shown in Table 19, indicates that in nearly all cases the mean scuff on the pitted teeth, at a time two hours prior to the occurrence of a "B" pit, was considerably higher than the mean scuff of the nonpitted teeth at the time that the pit was first observed. Of 55 pits observed, 87 percent of these had a higher percent scuff two hours prior to pitting than the mean scuff of the nonpitted teeth at the time of the occurrence of the "B" pit. From this, the mean scuff on the pitted teeth two hours prior to pitting was found to be, on the average, 161 percent of the value of the mean scuff of the nonpitted teeth. Since it is to be expected that the rate of scuffing might be increased once pitting has occurred[11.09], the rated scuff of the pitted tooth is not considered significant although this value is included in Table 19 for sake of comparison.

In order to further substantiate this analysis, the raw data from earlier fatigue studies at 165°F[11.09] were examined. This analysis included 30 of the reported tests with 276 "B" pits recorded. Of the teeth having "B" pits, 67 percent had a larger amount of scuff two hours before pitting than the mean scuff of the nonpitted teeth at the time of the occurrence of the pit and only 29 percent of the pitted teeth had values of scuff below this

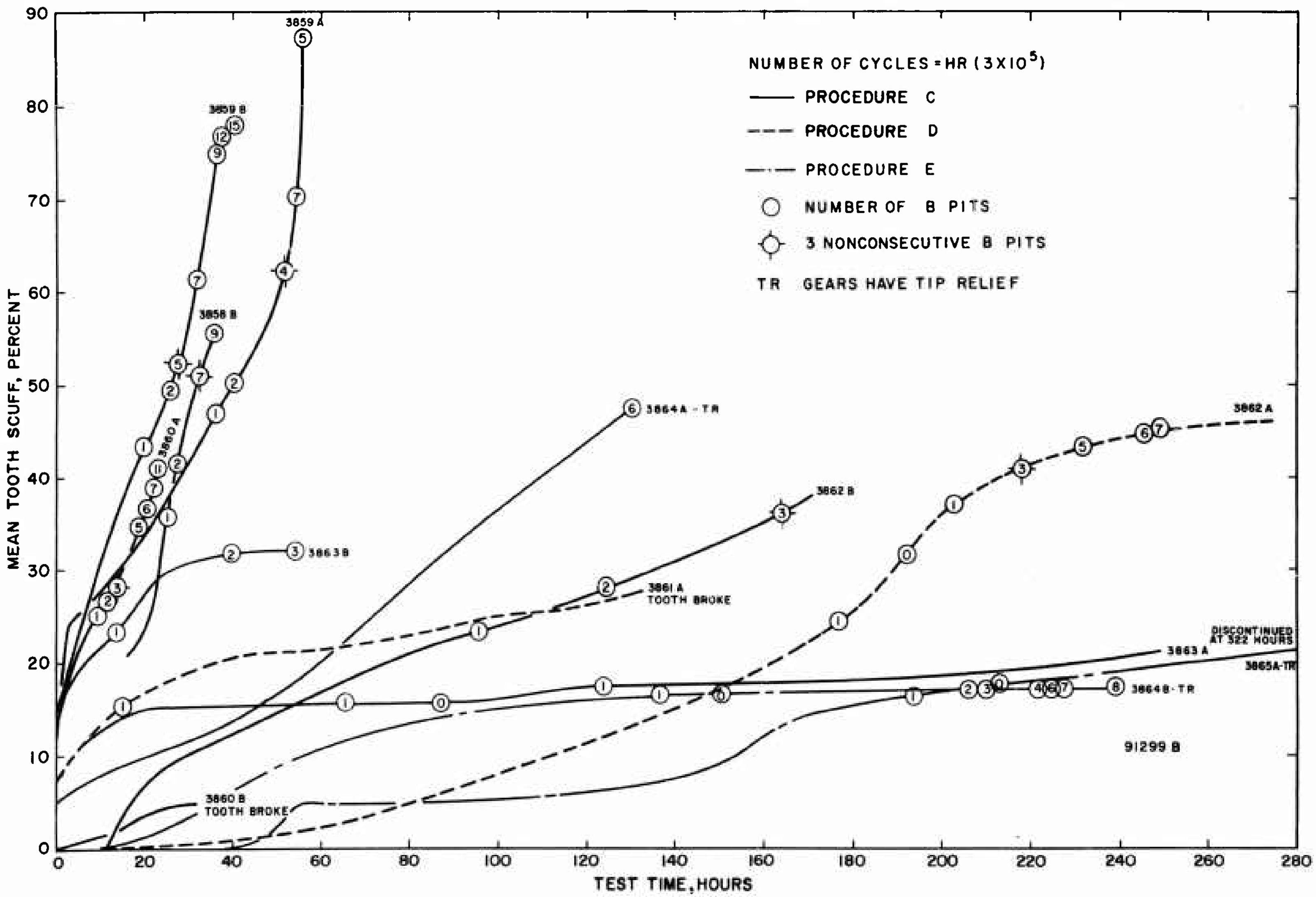


FIGURE 22. DEVELOPMENT OF PITTING AND SCUFFING WITH TIME

TABLE 19. COMPARISON OF THE SCUFF RATINGS OF PITTED AND NONPITTED TEETH

Test No.	Time of "B" Pit	Mean Scuff on NonPitted Teeth, %		Mean Scuff on Pitted Tooth, %	
		2 Hours Before Pitting	At Time of Pit	2 Hours Before Pitting	At Time of Pit
3858B	26	34	35	75	85
3858B	28	35	38	75	85
3858B	32	45	38	55	55
3858B	32	45	38	85	90
3858B	32	45	38	90	100
3858B	32	45	38	90	95
3858B	32	45	38	90	90
3858B	34	38	42	90	95
3858B	36	42	61	65	85
3858B	36	42	61	95	100
3859A	36	44	43	80	80
3859A	40	38	40	80	85
3859A	52	53	56	95	95
3859A	52	53	56	85	90
3859A	54	56	70	80	90
3859A	54	56	70	80	95
3859A	54	56	70	95	100
3859B	20	41	44	25	25
3859B	26	47	50	70	70
3859B	28	50	56	45	50
3859B	28	50	56	70	80
3859B	28	50	56	20	20
3859B	32	56	62	80	80
3859B	32	56	62	65	75
3859B	36	66	72	80	85
3859B	36	66	72	60	65
3859B	38	72	73	80	85
3859B	38	72	73	85	85
3859B	38	72	73	90	100
3859B	40	73	72	80	80
3859B	40	73	72	80	80
3859B	40	73	72	85	85
3860A	10	27	26	55	55
3860A	12	26	25	50	50
3860A	14	25	25	30	50
3860A	16	25	26	40	40
3860A	18	26	26	35	35
3860A	20	26	27	40	40
3860A	22	27	29	25	30
3860A	24	29	29	30	40
3860A	24	29	29	35	35
3860A	24	29	29	40	40
3860A	24	29	29	20	20
3861A	16	15	15	35	35
3862A	176	20	20	20	20
3862A	204	39	37	90	90
3862A	218	38	36	80	80
3862A	218	38	36	100	100
3862A	230	36	36	100	100
3862A	232	36	34	100	100
3862A	246		29	95	95
3862A	248	29	28	80	95
3862A	262	31	30	70	70
3862B	96	23	22	55	55
3862B	124	25	26	20	30

All tests performed using WADD high-temperature gear machine No. 1

figure; the remaining 4 percent remained at the same value. For this earlier work, the percent scuff on the pitted teeth at a time two hours prior to pitting was an average of 165 percent of the value of the mean scuff of the nonpitted at the time of pitting. These data indicate that teeth that have excessive scuff are more prone to pitting than teeth which have low values of scuff.

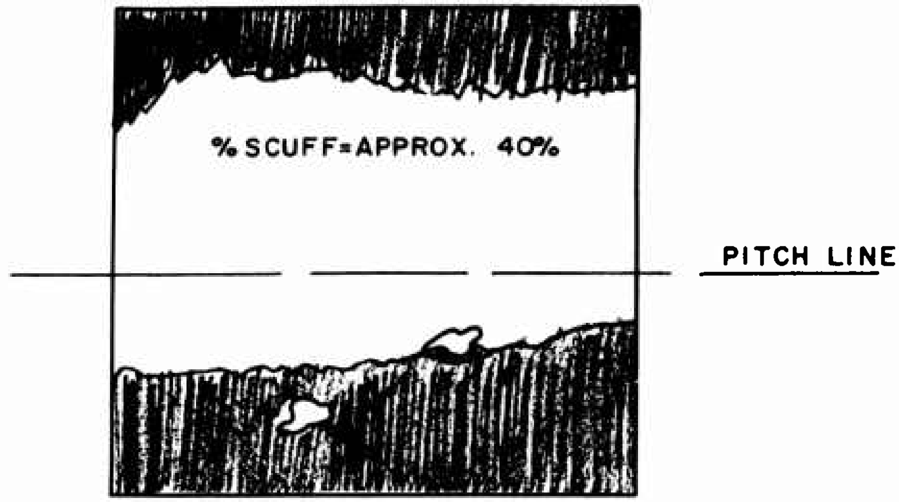
Based on these findings, in the present and earlier work, it is felt that the possibility of a relationship between the degree of pitting and excessive scuff is clearly indicated. Although it is not possible to clearly determine the reason for this relationship, it is suggested that excessive scuff might change the profile of the tooth enough to increase the tooth loading for a small area of tooth surface. As this would increase the effective load of that portion of the tooth surface, it is not unreasonable to expect that surface pitting would occur prematurely.

In addition to the relationship between scuff level and pitting, the location of a "B" pit on the tooth face in relation to the scuff present was also considered. In the tests prior to Test 3864B-TR, the occurrence of a "B" pit was always in the area immediately adjacent to or encompassed by the scuffed portion of the tooth face which was usually below the pitch line. In Test 3864B-TR this was not the case. The scuff on the pitted teeth was no higher than the mean scuff on the nonpitted teeth, and the pits observed were well removed from the scuff perimeter. A comparison of the two cases is shown in Figure 23.

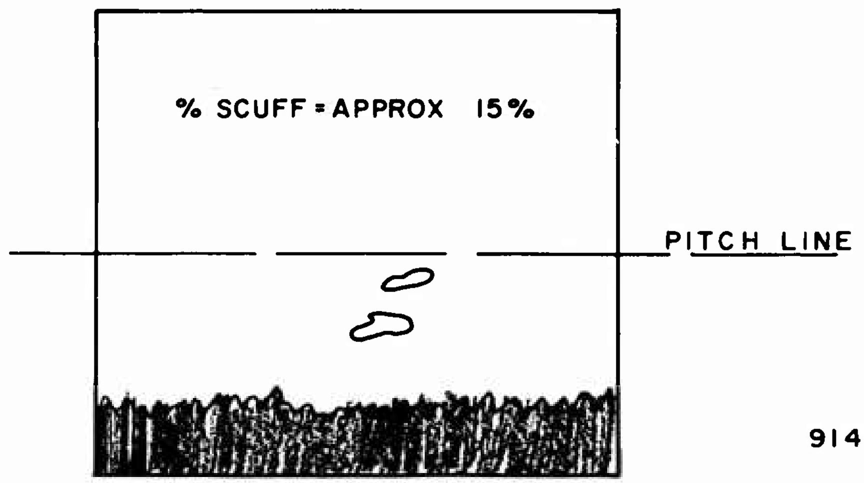
In the development of fatigue test procedures, it is important that the fatigue performance of the lubricant-gear combination is not masked significantly by other factors which are likely to affect fatigue. From the foregoing discussion, it is clear that if the general scuff level was high, then those teeth with high scuff were more prone to develop pitting and the pitting usually occurred within the scuffed area. On the other hand, if the general scuff level was low, then pitting appeared to develop in areas outside of the scuffed region, and the incidence of pitting in this case could not have been related to scuffing. Although the data obtained so far are extremely limited, it appears that the use of tip-relieved gears, or of low tooth load, helped to lower the general scuff level before pitting occurred and that the scuff that was obtained could not have hastened the occurrence of pitting. It is suggested that these conditions should be further investigated, with a view to developing a satisfactory fatigue test procedure.

4. Measurement and Monitoring of Test Gear Blank Temperature

The gear-blank temperature was measured and recorded during the fatigue determinations by use of an infrared radiometer in conjunction



A. FOR TESTS IN WHICH THE MEAN SCUFF IS GREATER THAN 20%, PITTING OCCURS AT THE PERIMETER OR IN THE SCUFFED AREA BELOW THE PITCH LINE.



91400B

B. FOR TESTS IN WHICH THE MEAN SCUFF IS LESS THAN 20 %, PITTING IS WELL REMOVED FROM THE SCUFFED AREA AND NEARER TO THE PITCH LINE.

FIGURE 23. COMPARISON OF RELATIONSHIP OF PIT LOCATION WITH RESPECT TO SCUFFED AREA OF GEAR TOOTH FACE

with a strip-chart recorder. A schematic diagram of the system is shown in Figure 7. The millivolt output of the radiometer is recorded by the recorder. Temperature data are then obtained by the use of a calibration curve. It was found that the gear-blank temperature did not rise above 400°F during loading or during the endurance runs. Previously, during lubricant scuff-limited load studies, increases in gear-blank temperature of the order of 100°F were experienced. Since the only deviations in test conditions between the scuff-limited load and fatigue procedures was speed and manner of lubrication, it is felt that the gear-blank temperature was controlled at 400°F by one or both conditions. By reducing the gear speed, the tooth stress and oil film shear, factors determined as having influence on the gear-blank temperature, were quite naturally reduced. In addition, by increasing the test oil flow rate and directing the test oil onto the meshing side of the gear teeth, a large amount of heat was carried away from the gear blank by the test oil. The latter conditions are believed to be the largest contributing factor in controlling the gear-blank temperature, since it was found inadvertently by a failure of the test oil pump, during a fatigue test, that a reduction in test oil flow rate to approximately 300 ml/min produced an immediate increase in gear-blank temperature as well as an increase in scuff.

5. Case Thickness Measurements of SwRI Design Nitralloy N Test Gears

In a further effort to determine the reason for the large deviations in time to limiting pitting, the case thickness of several of the used SwRI design Nitralloy N gears was determined by use of a Tukon microhardness tester. Three teeth approximately 120° apart were removed from the gear and the side of each tooth was ground to a depth of approximately 0.06 in. Figure 24 shows the manner and area of the gear tooth in which the measurements were made. A summary of the results is shown in Figure 25. It can be seen that the case thickness is between .018 and .025 in. and that there appears to be no appreciable difference in hardness between the gears examined.

6. Test Oil Consumption and Deterioration.

A careful record was kept of the consumption rate and changes of neutralization number and viscosity of the test oil during most of the fatigue tests. When samples of the test oil were removed during a test, an equivalent amount of fresh oil was added equal to the amount of oil sample removed. In all cases the volume of oil added during a test was small (about 50 ml/hr on the average); no appreciable effect on the viscosity and neutralization number of the test oil was noted. A complete change of test oil was

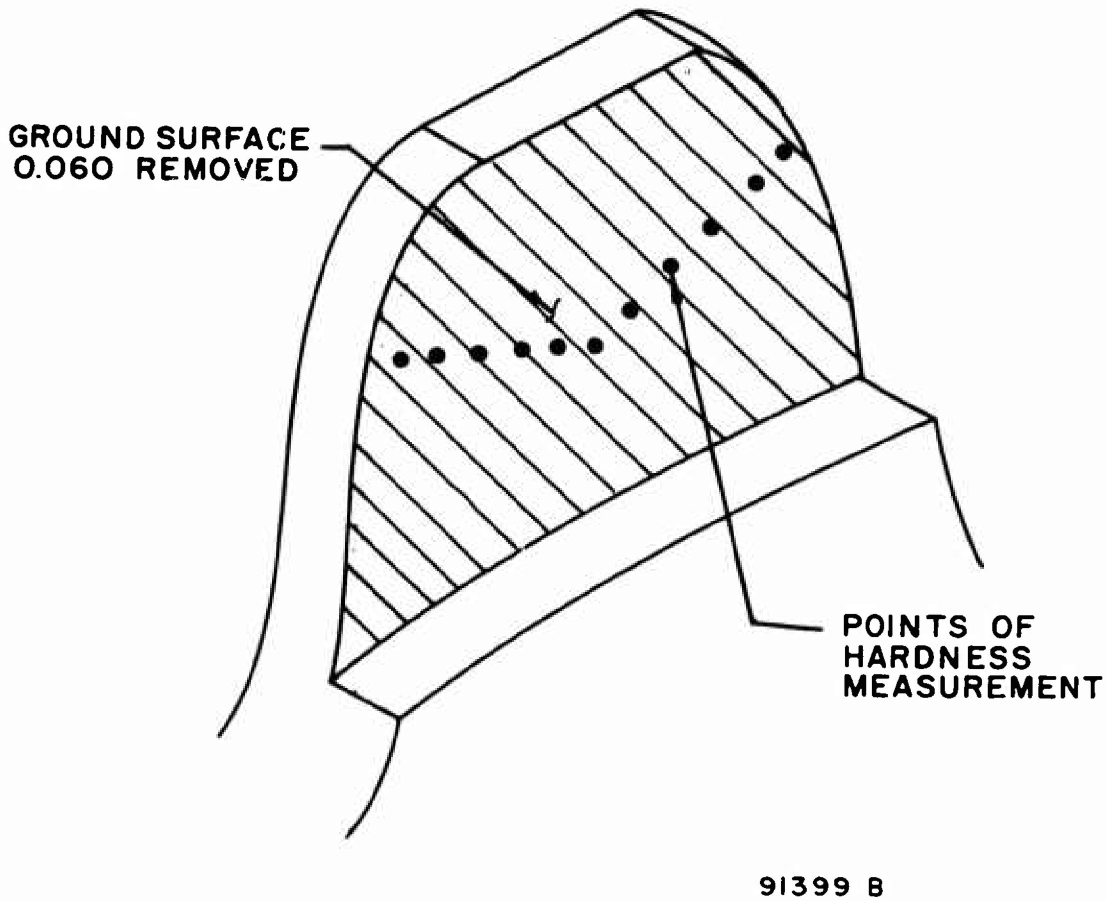


FIGURE 24. ILLUSTRATION OF GROUND GEAR TOOTH PREPARED FOR KNOOP HARDNESS DETERMINATIONS

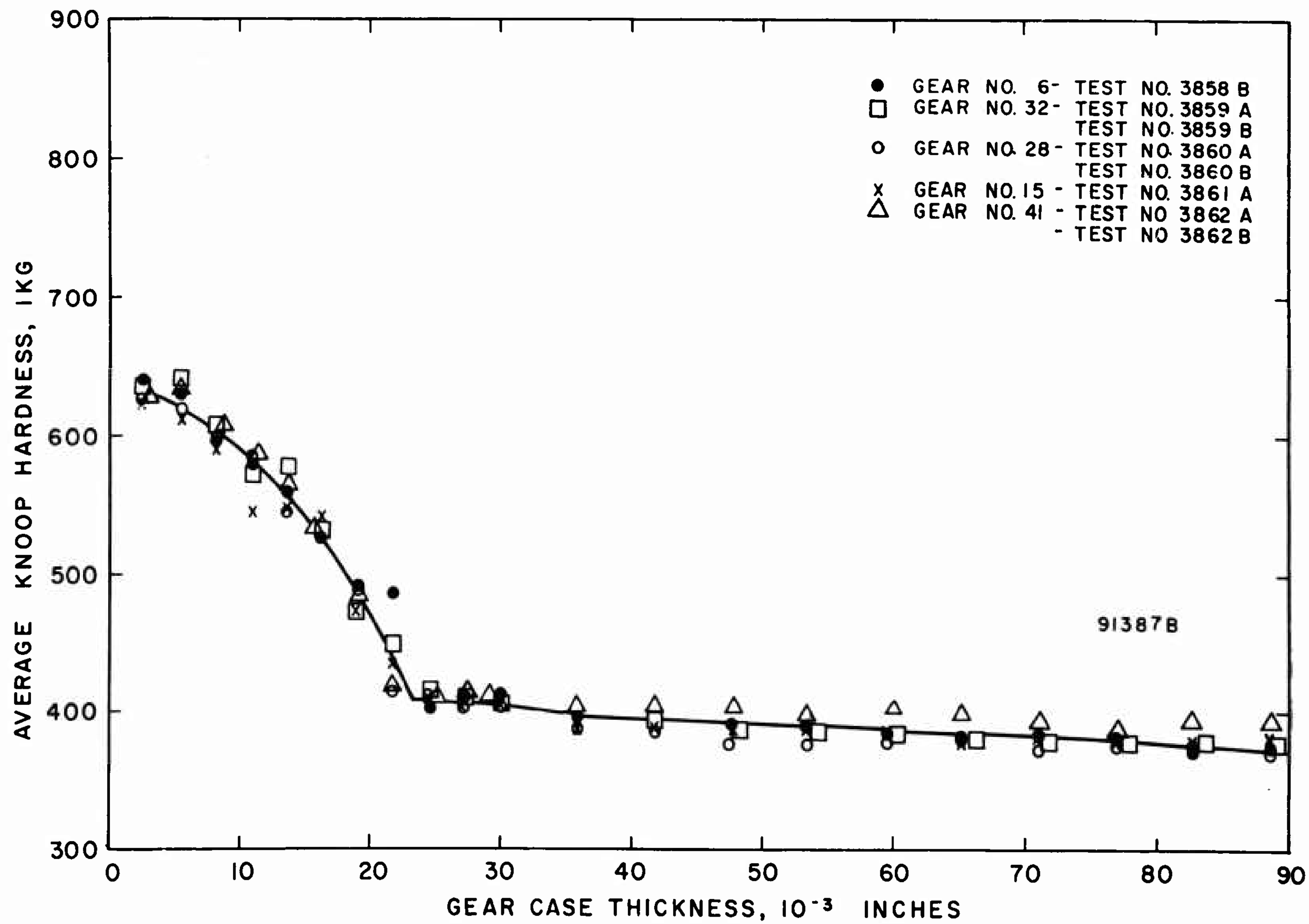


FIGURE 25. CASE THICKNESS MEASUREMENTS OF SwRI DESIGN NITRALLOY N STEEL GEARS

made when an increase in the neutralization number of approximately 1.0 mg KOH/g was obtained during a test. The rate of consumption and change of viscosity and neutralization number were computed and are presented in Table 20.

E. Conclusions

On the basis of the load-carrying capacity determinations of ten lubricants, it was found that no organized correlation existed between the results obtained with one gear material under a given set of operating conditions and those obtained with another gear material under another set of operating conditions.

The rating level of the 165°F load-carrying capacity test using the WADD high-temperature gear machine was comparable to that of the standard 165°F load-carrying capacity test using the standard Ryder gear machine.

The repeatability and reproducibility of the 165°F load-carrying capacity test using the WADD high-temperature gear machine were comparable to those of the standard 165°F load-carrying capacity test using the standard Ryder gear machine.

The repeatability and reproducibility of the 400°F load-carrying capacity test using the WADD high-temperature gear machine were inferior to those of the 165°F test.

In view of the comparable scuff ratings obtained between the closed-circuit television and the visual-microscopic gear inspections, it is concluded that gear inspection by closed-circuit television is acceptable both from the standpoint of accuracy and from the standpoint of safety of operation.

The feasibility of using infrared radiometry in the measurement of gear-blank temperatures has been demonstrated. From the infrared radiation measurements made during the scuff-limited load tests, it was found that the gear-blank temperature increased with increase in scuffing level.

It has been found in the 400°F load-carrying capacity program that the scuff-limited load results obtained with the gear-blank temperature controlled at 400°F were higher than the results obtained using the standard 400°F test procedure.

TABLE 20. SUMMARY OF TEST OIL CONSUMPTION AND DETERIORATION DATA

Test Number	Total Test Time, hr	Avg. Time of T. O. Change, hr	Test Oil Consumption: Total Oil Consumed, ml	Test Oil Consumption: Consumption Rate, ml/hr	Test Oil Deterioration: Viscosity Change, cs/hr	Test Oil Deterioration: Neut. No. Change, mg KOH/g/hr
3858B	20	20	--	--	0.110	0.065
3859A	55	55	--	--	0.132	0.086
3859B	40	40	--	--	0.036	0.018
3860A	24	24	--	--	0.033	0.013
3860B	32	32	--	--	0.072	0.028
3861A	132	56	--	--	0.045	0.016
3862A	274	48.5	16,614	61	0.037	0.016
3862B	160	52	10,730	69	0.065	0.018
3863A	206	41.2	19,570	95	0.012	0.022
3863B	54	49.0	4,320	80	0.091	0.014
3864A	106	53.0	7,570	71	0.038	0.011
3864B	208	49.5	14,100	68	0.044	0.017

The existence of a relationship between the initial incidence of pitting and excessive scuffing has been indicated. However, at low scuff level, the pitting did not appear to be related to scuffing.

Though the fatigue data at this time are somewhat limited, it is believed that the use of tip-relieved test gears in conjunction with a low tooth load to give a low general scuff level holds promise for further studies.

III. BEARING LUBRICATION

A. General Remarks

Bearing lubrication research in the present program has been concerned with the effect of lubricant variables on rolling-contact bearing fatigue and other modes of lubricant failure under extreme conditions of loads, speeds and temperatures. The program was divided into two principal tasks, one involving the operation of small (20-mm bore) M-50 steel, angular-contact ball bearings at relatively light thrust loads but high speeds, and the other involving operation of relatively large (85-mm bore) M-50 steel, angular-contact ball bearings at moderate speeds but high thrust loads. In both cases, high operating temperatures were imposed upon the test bearing and the test lubricant. The 85-mm ball bearings were selected as being representative of the thrust bearings in gas turbine or jet engines. The 20-mm ball bearings were selected as being typical of those used in flight vehicle power units.

Full-scale tests of lubricant-bearing combinations are generally expensive to conduct and the results difficult to interpret, and yet some means must be had whereby obviously unsuitable materials proposed as lubricants may be removed from those worthy of closer examination without sacrifice of labor and materials. Simulated testing has long been the answer given to this problem, and under proper conditions can be expected to yield results comparable to those obtained in full-scale tests. The choice of proper conditions is often difficult to make and frequently, unless basic mechanisms are understood, is the result of estimates.

The 85-mm thrust bearing lubrication research program has been primarily concerned with an investigation of the effect of lubricants on rolling-contact bearing fatigue at a lubricant supply temperature of 425°F, and a bearing outer-race temperature of 525°F. Two test procedures, one a constant-load procedure and the other a step-load procedure, were employed to effect bearing fatigue failures. The step-load procedure was investigated in an effort to bring about bearing fatigue failures in a shorter period of time than that encountered with the constant-load test procedure. However, a statistical analysis of all of the data obtained during seven tests using the constant-load procedure and ten tests using the step-load procedure indicated that the two test procedures did not produce results that could be correlated.

The 20-mm thrust bearing lubrication research program has been concerned with an investigation of the performance and deterioration characteristics of lubricants in the temperature range of 500 to 700°F. A large number

of bearing and test rig failures which could not be ascribed to the test lubricant precluded clear-cut indications of the performance capabilities of the lubricants tested. Therefore, design changes were adopted in an endeavor to eliminate these failures. These design changes, however, introduced unexpected and undesirable temperature control problems which are currently being investigated.

B. 85-mm Thrust Bearing Test Equipment

1. 85-mm Thrust Bearing Machine

The 85-mm thrust bearing machine was developed under the previous contract and has been therein described.[0.85] However, it is believed that a review is in order. Figure 26 shows a cross section of the 85-mm bearing machine. Note that the inner races of the two test bearings (A and B) are clamped to a cylindrical adaptor that turns with the cantilevered shaft-end. The cylindrical case of the bearing head is supported by the outer races of these bearings and is restrained from turning with the shaft only by a torque arm (not shown) which is attached to a torque-measuring device[11.10] as shown in Figure 27.

Referring again to Figure 26, note that load is applied to the test bearings by means of hydraulic pressure acting on a thin steel diaphragm C, which in turn presses against the loading sleeve D. The diaphragm has an annular convolution near its edge to insure flexibility. In order for bearing A to take the load, its outer race must slide freely. Since bearing B must balance the thrust applied to bearing A, the two bearings become equally and oppositely loaded.

Test lubricant is introduced to the loaded side of the inner races of the test bearings by means of a double jet E, and is removed from the head through the port F which leads to a scavenge pump. Leakage around the shaft is prohibited by the slinger and nonrubbing seal assembly G. In normal operation, the vent hole located on the top of the ring H is open to the atmosphere, and movement of air acts to pump the test oil back to the bearing head, and also to pump any support oil that passes the support bearing back to the support section. In case it is desired to operate the test bearings in an inert gas atmosphere, all that is necessary is to apply a slight pressure of the inert gas to the vent. Positive seal against air leakage is accomplished, in that event, by the use of an elastomer "O" ring, which is held between the rings H and I. The lower hole on ring H is to facilitate draining; it may be closed or left open as necessary.

Thermocouples are placed 120 degrees apart on the outer race of each test bearing with one located at the bottom. The outer races may be heated, if necessary, by means of cartridge heaters (J) disposed around the

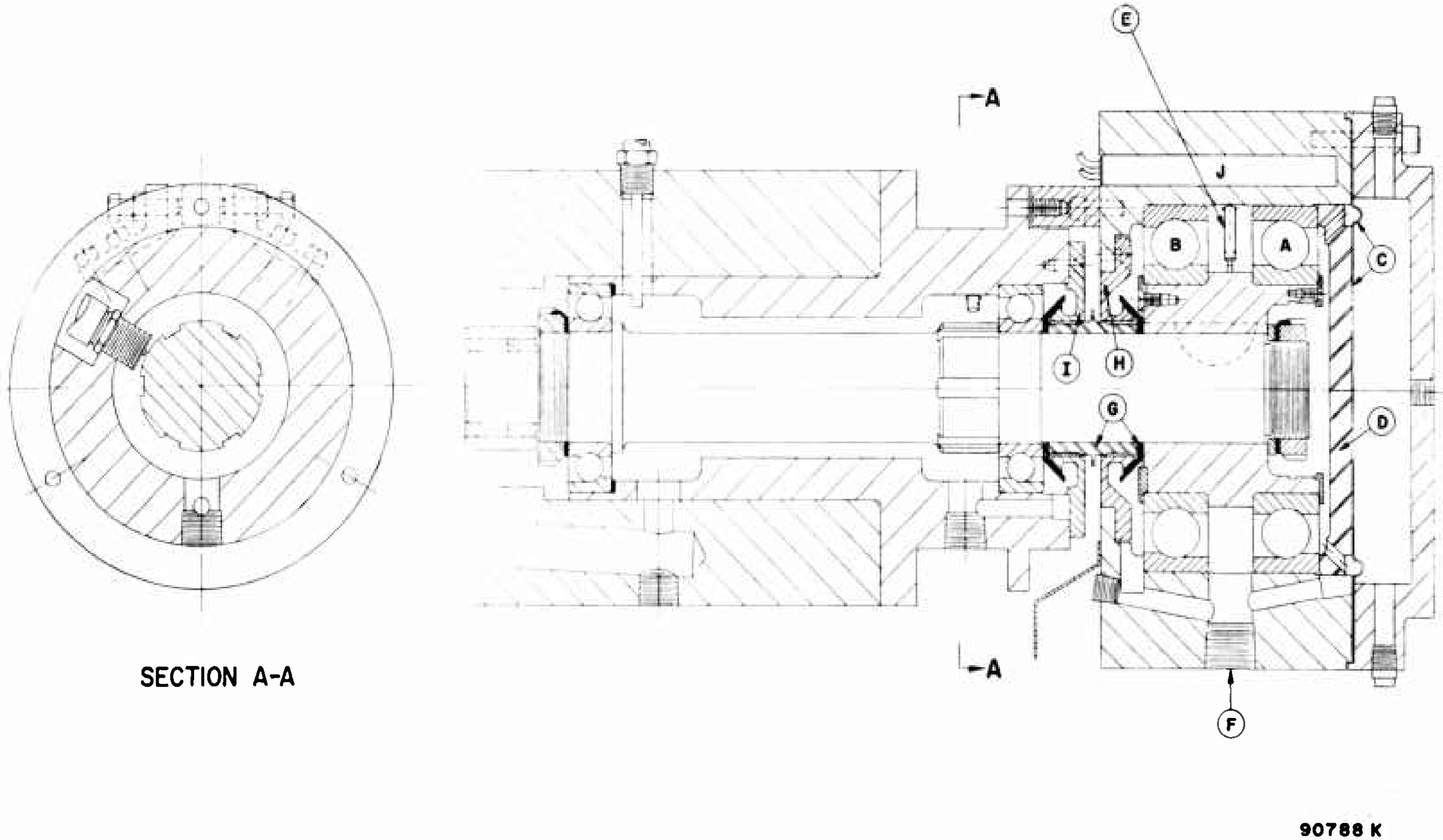


FIGURE 26. CROSS SECTION OF 85-MM THRUST BEARING MACHINE

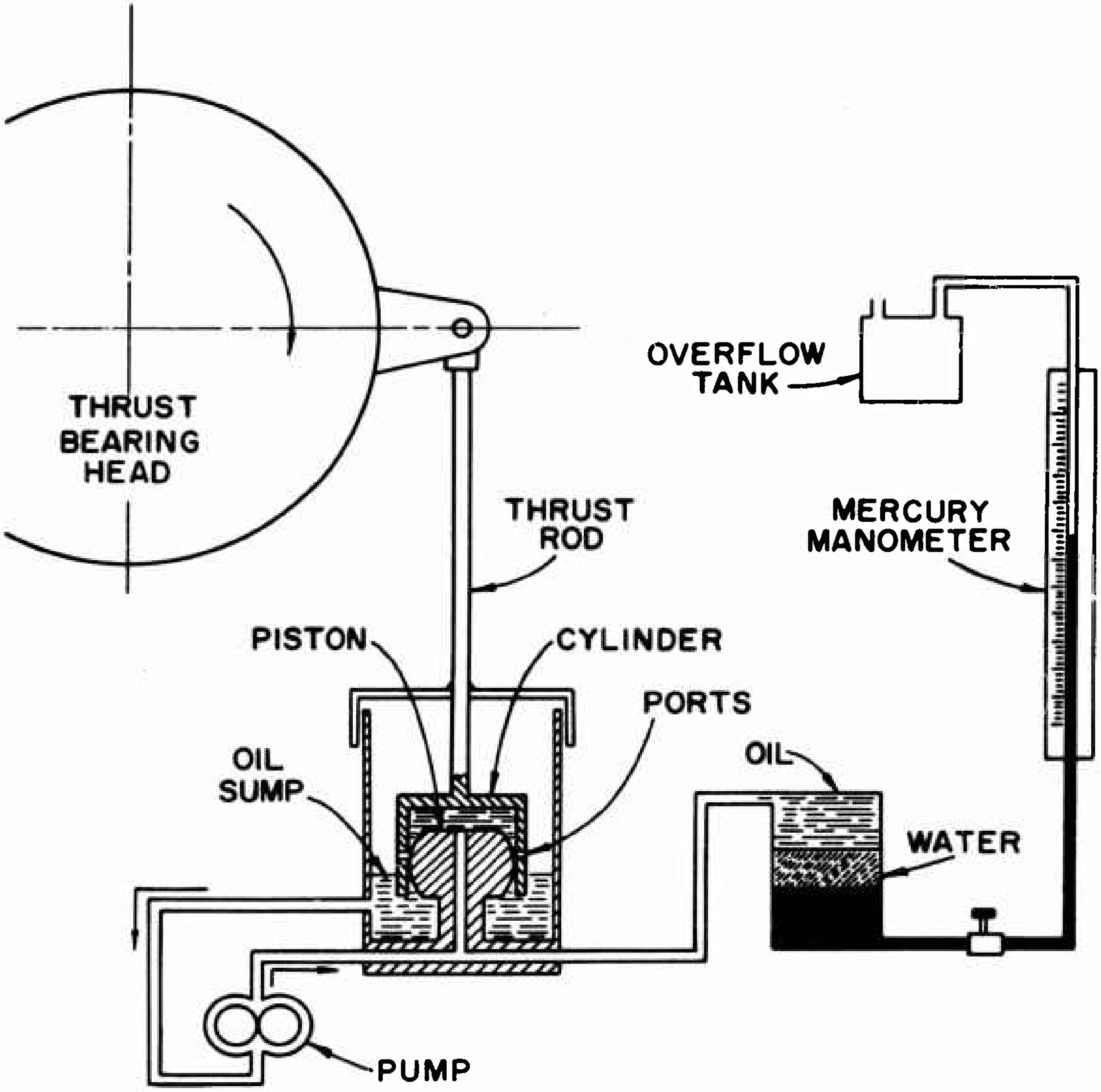


FIGURE 27. SCHEMATIC DIAGRAM SHOWING PRINCIPLE OF M.I.T. HYDRAULIC SCALE FOR TORQUE MEASUREMENT

periphery. Under either heated or unheated conditions, the temperatures of the two outer races have been found to be practically equal. This may be explained by the fact that the bearing head is thermally well-isolated from the support system, except for the shaft which has a rather small cross section. The small heat loss also explains why the power consumption of the heaters has been very moderate even for temperatures as high as 800°F.

The machine may be operated optionally at speeds up to 15,000 rpm, which corresponds to a DN value of 1.275×10^6 mm-rpm. The maximum thrust load capability is of the order of 20,000 lb, which far exceeds the nominal load-carrying capacity of the test bearings.

Calibration of Thrust Load. In order to assure uniformity of load conditions, it was necessary to establish a calibration curve of thrust load as a function of hydraulic pressure, which would be independent of any initial diaphragm displacement within the dimensional limits of assembly.

As shown in Figure 26, the thrust load is applied to the test bearings by means of a hydraulic pressure acting on a thin steel diaphragm C, which in turn presses against the loading sleeve D.

In order to calibrate the loading system, a set-up shown in Figure 28 was used. The load sleeve from the particular test machine being calibrated was placed in its test head along with the pressure diaphragm. The entire unit was placed on the bed of a hydraulic testing machine for loading. The load was applied to the sleeve through a hemispherical ball joint to minimize binding. Hydraulic pressure was directed onto the under side of the diaphragm to oppose the load. In order to determine what, if any, effect initial diaphragm displacement would contribute to the calibration, the loading procedure was made for initial diaphragm displacements of from 0.005 in. to 0.040 in. Within the limits of experimental error, no effect was noted. Figure 29 presents the average load calibration curve obtained for the 85-mm thrust bearing machines. This curve represents an average of five different loading sequences.

2. High-Temperature Test Oil System

The high-temperature test oil system is shown schematically in Figure 30. Note that the oil is pumped from the sump by a submerged pump, from which it passes to a "tee," one branch of which goes to a bypass valve and the other goes to a filter. From the filter, flow passes to a sampling valve which may be used to switch from the main jet to a dummy set for sampling and flow checking. The scavenge line from the bearing head returns to a submerged scavenge pump, which discharges directly into the sump.

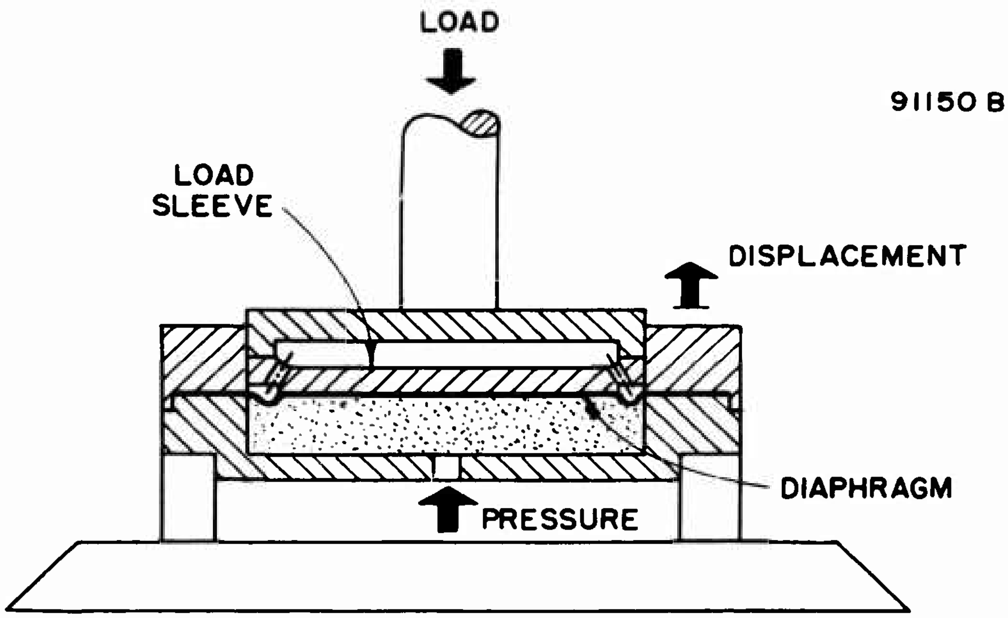


FIGURE 28. SCHEMATIC DIAGRAM OF 85-MM THRUST BEARING LOAD CALIBRATION APPARATUS

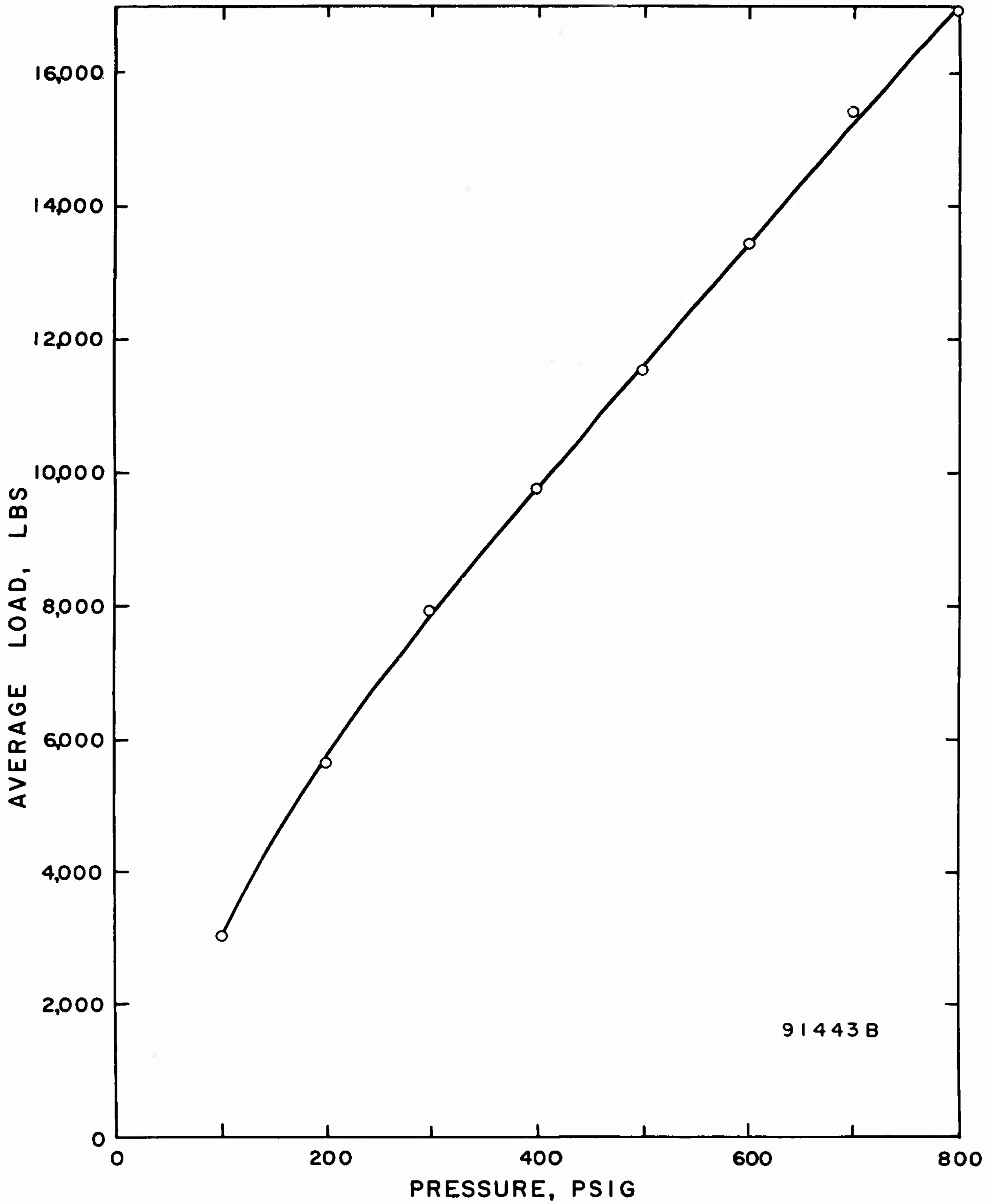


FIGURE 29. AVERAGE LOAD CALIBRATION CURVE OBTAINED FOR 85-MM THRUST BEARING MACHINE

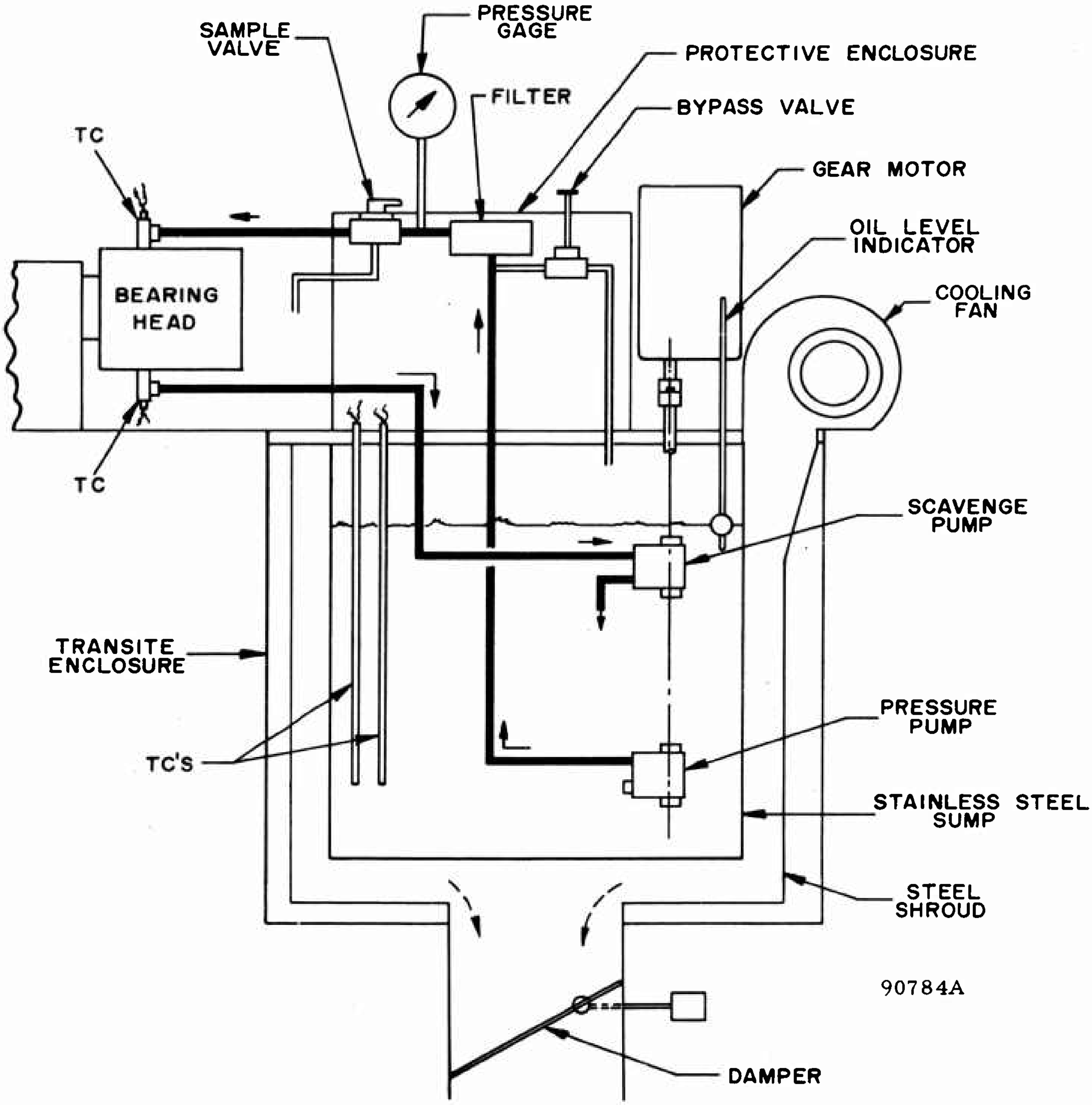


FIGURE 30. SCHEMATIC DIAGRAM OF HIGH-TEMPERATURE TEST OIL SYSTEM

Oil level is measured by a float (which has a hollow tube as a stem to permit expansion of entrapped air). A scale behind the float is marked by the operator for each test condition, indicating both cold volume and hot volume for the given oil, thus providing guides for cold filling and for make-up addition during a run.

The cabinet which contains the sump is made of transite, with removable panels for accessibility. Within this cabinet is a permanently installed steel shroud which surrounds the sump and which has attached to it strip heaters, their function being only to minimize heat loss from the sump. This shroud is also wrapped with rockwool and aluminum foil insulation to cut heat loss to a minimum. In order to provide temperature control, a cooling fan actuated by an on-off controller blows room air into the cavity between the sump and shroud. This air leaves through an opening at the bottom of the cabinet, which opens when the fan is turned on, and closes when the latter is off in order to prevent unwanted air circulation by a "chimney effect."

Test oil samples are taken in a stainless steel beaker. The oil consumption is determined by weighing, since the volume changes rapidly upon cooling when the sample is drawn at high temperature.

Some component details are of significance and these are outlined below.

Pumps. Brown and Sharpe No. 2 pumps with Graphalloy bushings, modified for tandem mounting are used. They are driven by a 1/3-hp gear motor at approximately 500 rpm.

Filter. The filter used has 100-mesh screen. It is enclosed in a steel housing, and uses stainless steel "O" rings.

Sample Valve. A G. W. Dahl, 3-way, diaphragm valve has been modified for this application by replacement of all parts which will not withstand high temperatures. Plug valves have been found to be inoperative when subjected to extreme test conditions over long periods of time.

Lines to Bearing Head. Teflon-cored flex-lines have been found to give adequate service up to about 600°F oil-in temperature. They were found to fail near 700°F, and have been replaced by steel lines for such high-temperature applications.

Safety Precautions. All lines are shielded, and all major portions of plumbing are placed in a metal cabinet above the sump. This also accomplishes the purpose of thermal insulation along with personnel protection, and has led to temperature drops between the sump and jet varying in

almost linear fashion up to 21°F drop for 700°F oil-in and 800°F bearing temperatures.

3. High-Temperature 85-mm Test Bearings

The test bearings are angular-contact ball bearings, type AAMM 217-4 MMR, made by Fafnir Bearing Company to ABEC-7 tolerances from a single heat of consumable electrode M-50 steel. The major dimensions of the bearings are:

Inside diameter, mm	85
Outside diameter, mm	150
Bearing width, mm	28
Ball complement	15
Ball diameter, in.	13/16
Contact angle, degree	25
Race curvature, %	52

The bearings are of split inner race design; and the retainer, of S-monel metal, is piloted on the outer race. The balls and retainer assembly may be replaced by a new assembly after a test. This is possible since only one side of the outer race and one side of the inner race are affected in a given test; thus the unused sides of each race may be utilized for another test.

Test Bearing Designation. Specific designation of test bearings is essential to a clear presentation of fatigue data. The system which was adopted gives a designation to each of the inner races of a test bearing; the same designations are given to the outer races such that the outer race-inner race combination, which carries the load on a particular test, will have the same designation.

Each designation is composed of three parts: a number, a letter, and then another number. The first number indicates a series of tests, the letter indicates a particular bearing within the series of tests, and the final number indicates a particular outer race-inner race combination on the given bearing. For example, the designation 1-B-2 indicates a series of tests which have been given the number one, bearing B within the series of tests, and the particular outer race-inner race combination, number two.

C. Bearing Fatigue Investigations with 85-mm Thrust Bearing Machine

The objective of the 85-mm thrust bearing program was to develop an apparatus and test technique to evaluate lubricants for use in gas turbine or jet engines with emphasis on bearing fatigue and wear.

A program for the development of a suitable test procedure has been completed using GTO-915 and GTO-950 (different batches of a MIL-L-9236B type lubricant). Under this program, a constant-load test procedure and a step-load test procedure were studied. With the constant-load test procedure, the bearings were tested under specified conditions with a constant value of thrust load applied. With the step-load procedure, the same test conditions were maintained, but the applied thrust load was increased at given time intervals.

The results obtained using the constant-load and step-load procedures have been compared statistically in an effort to obtain a correlation of the results produced by the two different test procedures. This comparison is discussed in a subsequent section.

1. Constant-Load Bearing Fatigue Program

In the constant-load bearing fatigue program, seven bearing fatigue failures were obtained using the following test conditions:

Bearing outer-race temperature, °F	525
Oil-in temperature, °F	425
Bearing speed, rpm	10,000
Thrust load, lb	9,785
Oil flow rate (per bearing), ml/min	1,200
Test duration	To failure
Interval for viscosity, neutralization number and oil consumption check, hr	5

In addition, a complete change of test oil was made whenever the viscosity increased to twice the value for fresh oil.

Table 21 presents a summary of the results obtained using the constant-load test procedure, including a description of each of the fatigue failures encountered. It will be noted that the total test time for the seven tests varied from 159 to 564 hours. The criterion used to determine each bearing failure was an increase in the noise level of the machine followed by a visual inspection of the test bearings.

Lubricant samples were taken at five-hour intervals during all tests. For each of these samples, laboratory analyses were made to determine viscosity and neutralization number. Table 22 presents an indication of the average performance of the test lubricant at various stages of deterioration. These data represent an average of eight complete oil runs, as well as several incomplete runs, in which the viscosity increased to approximately twice the value for the fresh oil.

TABLE 21. CONSTANT-LOAD 85-MM BEARING FATIGUE DATA ON GTO-915 AND GTO-950

Bearing Designation	Total Test Time to Failure, hr	Description of Failure
1-A-1	159	Inner race lightly pitted. All balls showed galling; several balls lightly pitted. Sporadic pitting of outer race.
1-A-2	463	Sporadic pitting and extensive plastic flow of metal on inner race. Moderate pitting of four balls. Cage broken.
1-B-1	460	Sporadic pitting and extensive plastic flow of metal on inner race. All balls showed galling.
1-B-2	212	Sporadic pitting and extensive plastic flow of metal on inner race. One moderate pit on outer race.
1-C-1	165	Inner race moderately pitted all around. Heavy pitting on one ball. Cage broken.
1-C-2	493	Inner race moderately to heavily pitted all around. One ball lightly pitted. One ball heavily pitted. Cage broken.
1-D-1	564	Moderate plastic flow of metal on inner race.

GTO-915 and GTO-950 are different batches of a MIL-L-9236B type lubricant. Test conditions were as follows: 10, 000 rpm, 9, 785 lb thrust load, 525°F bearing outer-race temperature, 425°F test oil-in temperature.

TABLE 22. VISCOSITY AND NEUTRALIZATION NUMBER DATA FOT GTO-915 AND GTO-950, CONSTANT-LOAD PROGRAM

Viscosity at 100°F

Initial Viscosity, cs	Average Time For 25% Increase in Viscosity, hr	Average Time For 50% Increase in Viscosity, hr	Average Time For 75% Increase in Viscosity, hr	Average Time For 100% Increase in Viscosity hr
16.0	51	82	104	114

Neutralization Number

Initial Neut. No., mg KOH/g	Average Neut. No. after 25% Increase in Viscosity, mg KOH/g	Average Neut. No. after 50% Increase in Viscosity, mg KOH/g	Average Neut. No. after 75% Increase in Viscosity, mg KOH/g	Average Neut. No. after 100% Increase in Viscosity, mg KOH/g
0.0	2.7	3.5	4.1	4.8

GTO-915 and GTO-950 are different batches of a MIL-L-9236B type lubricant. Average values are based on eight complete oil runs. Test conditions are given in Table 21.

2. Step-Load Bearing Fatigue Program

The advantage of the step-load procedure would be to obtain bearing fatigue in a shorter period of time than that encountered in the constant-load procedure; however, it is essential that a suitable means be available for a comparison of the data obtained from these two procedures. One way to do this is to compute an equivalent fatigue life for the step-load test on the basis of the applied load in the constant-load test. Within the normal range of bearing operation, it is generally agreed that the fatigue life of ball bearings varies inversely as the cube of the applied load.(11.11) Assuming the use of the "cube rule," the equivalent fatigue life L_F for a step-load test is given by the equation

$$L_F = L_{F_1}\left(\frac{P_1}{P}\right)^3 + L_{F_2}\left(\frac{P_2}{P}\right)^3 + L_{F_3}\left(\frac{P_3}{P}\right)^3$$

where P_1, P_2, P_3, ... are the step loads, L_{F_1}, L_{F_2}, L_{F_3} ... are the corresponding time intervals over which each step-load was applied, and P is the constant load for which the equivalent life is being computed. For this application, $P_1 = P$, $P_2 = 1.375\ P$, and $P_3 = 1.732\ P$, thus

$$L_F = L_{F_1} + 2.6 L_{F_2} + 5.2 L_{F_3}$$

In the step-load bearing fatigue program, ten bearing fatigue failures were obtained. The test bearings used were part of the same production lot as those used in the constant-load bearing fatigue program. The test conditions were the same as those used for the constant-load program except for the thrust load. The following thrust loads were used with the step-load procedure:

Thrust Load, lb	Bearing Time, hr
9,785*	50
13,430*	50
16,940*	To failure

* A recent calibration of the thrust load mechanism used on the 85-mm bearing machine has shown the figures used in previous reports (0.25, 0.26) to be incorrect. This has, of course, changed the coefficients used earlier in the "cube rule" relationship.

Table 23 presents a summary of the results obtained using the step-load procedure, including a description of each of the fatigue failures encountered. It will be noted that the equivalent test time at 9785 lb load (obtained by using the "cube rule" relationship) varied from 51 to 1532 hours.

Lubricant samples were taken in the same manner as described for the constant-load test procedure. Table 24 presents the average performance of the test lubricant at various stages of deterioration during the step-load fatigue tests. It will be noted that these average values are very comparable to the values obtained during the constant-load fatigue tests (see Table 22).

D. A Statistical Comparison of the Constant-Load and Step-Load Programs

Bearing fatigue test data may be presented graphically by the Weibull plot. This plot employs special coordinate scales which will generally give a straight line for fatigue data.

Figures 31 and 32 show, respectively, Weibull plots for the constant-load and step-load programs. Included are lines indicating the 90 percent confidence limits for these tests. The significance of the 90 percent limits is that 90 out of 100 times the true population of bearings will be represented, for any chosen value of percent failed, by a data point within the two lines. That all points fall within these 90 percent confidence lines is indicative that results are representative of the population from which the sample was drawn.

When one compares two processes or two batches, or any similar situation, it is in an endeavor to determine the superiority of one batch over another, or the difference in one process over another. In the particular case at hand, it is hypothesized that the step-load program gives different results from those obtained in the constant-load program, even though the bearings used for both tests were randomly chosen from a lot of bearings as nearly identical as is physically possible to achieve.

Prior to the examination of the above hypothesis, it is advantageous to examine the effect on the data resulting from the use of two machines to test the bearings.

Of the seven constant-load tests, four were made entirely on the No. 1 machine and three tests were made principally on the No. 2 machine. In particular, these three tests were started on the No. 1 machine and were completed on the No. 2 machine.

TABLE 23. STEP-LOAD 85-MM BEARING FATIGUE DATA ON GTO-950

Bearing Designation	Actual Test Time, hr At 9785 lb Load	At 13, 430 lb Load	At 16, 940 lb Load	Equivalent Test Time at 9785 lb Load, hr	Description of Failure
2-A-1	50	1-1/2	0	54	Plastic flow on outer and inner races. Balls pitted.
2-A-2	50	1	0	53	Races and balls moderately pitted. Cage broken.
2-B-1	50	1	0	53	Plastic flow on races. Balls galled.
2-B-2	50	1/2	0	51	Plastic flow and pitting of inner race.
2-C-1	50	50	220	1324	Inner race pitted.
2-C-2	50	50	12	243	Plastic flow on inner race.
2-D-1	50	50	260	1532	Races and balls pitted.
2-D-2	50	50	83	612	Outer race large pit, inner race small pits. Balls scratched.
2-E-1	50	50	124	825	Heavy pits on outer race. Slight on balls.
2-E-2	50	50	217	1305	Heavy pit on outer race. Badly scuffed cage.

Test conditions were as follows: 10, 000 rpm, 525° F bearing outer-race temperature, 425° F test oil-in temperature, step-loads of 9785 lb, 13, 430 lb, 16, 940 lb.

TABLE 24. VISCOSITY AND NEUTRALIZATION NUMBER DATA FOR GTO-950, STEP-LOAD PROGRAM

Viscosity at 100°F

Initial Viscosity cs	Average Time For 25% Increase in Viscosity, hr	Average Time For 50% Increase in Viscosity, hr	Average Time For 75% Increase in Viscosity, hr	Average Time For 100% Increase in Viscosity, hr
16.0	40	65	85	111

Neutralization Number

Initial Neut. No., mg KOH/g	Average Neut. No. after 25% Increase in Viscosity, mg KOH/g	Average Neut. No. after 50% Increase in Viscosity, mg KOH/g	Average Neut. No. after 75% Increase in Viscosity, mg KOH/g	Average Neut. No. after 100% Increase in Viscosity, mg KOH/g
0.0	3.0	3.5	3.9	4.2

Based on ten tests with a total of 13 complete oil changes. Values for 100% increase are average of 3 values. Test conditions in Table 23.

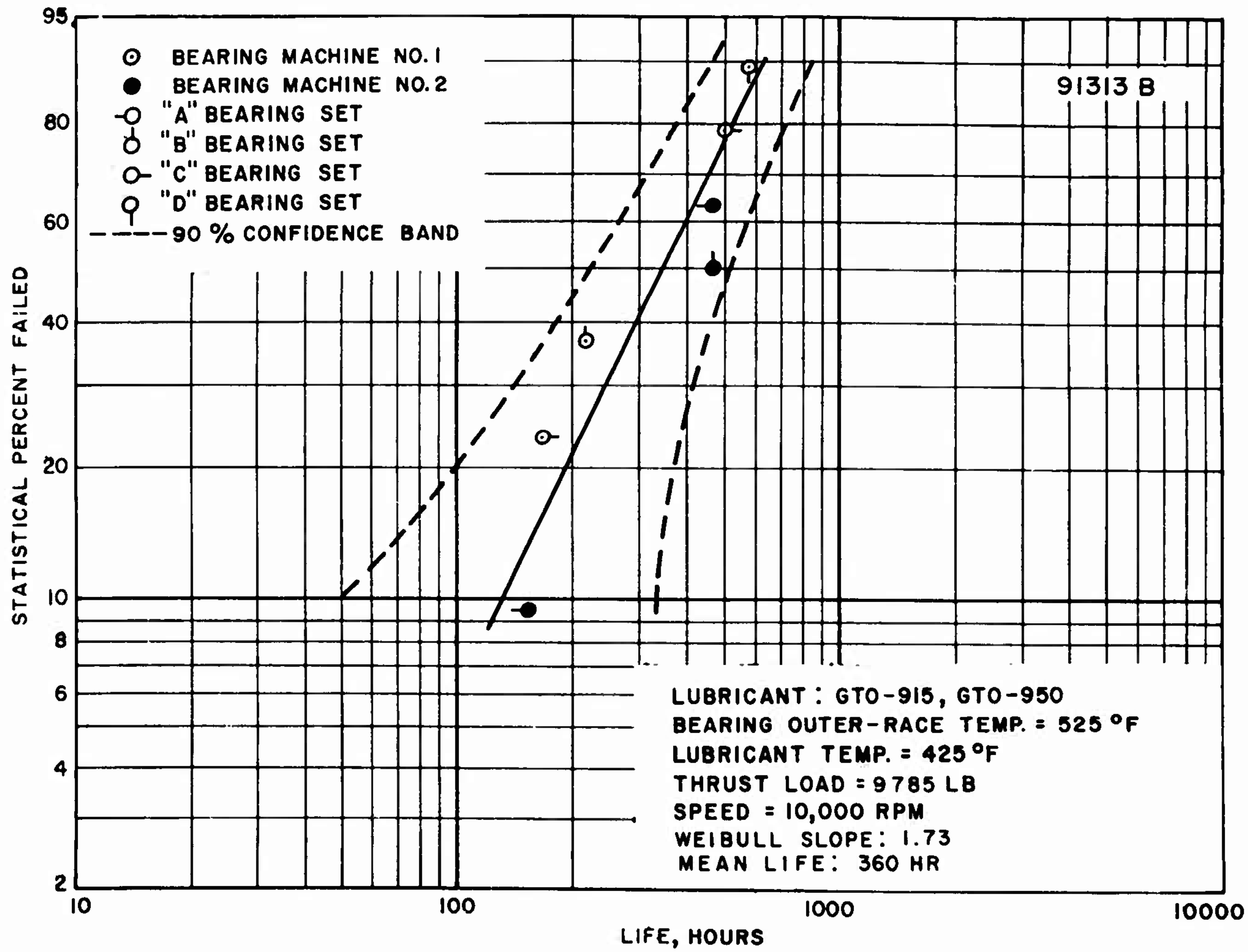


FIGURE 31. WEIBULL PLOT FOR CONSTANT-LOAD 85-MM THRUST BEARING FATIGUE DATA

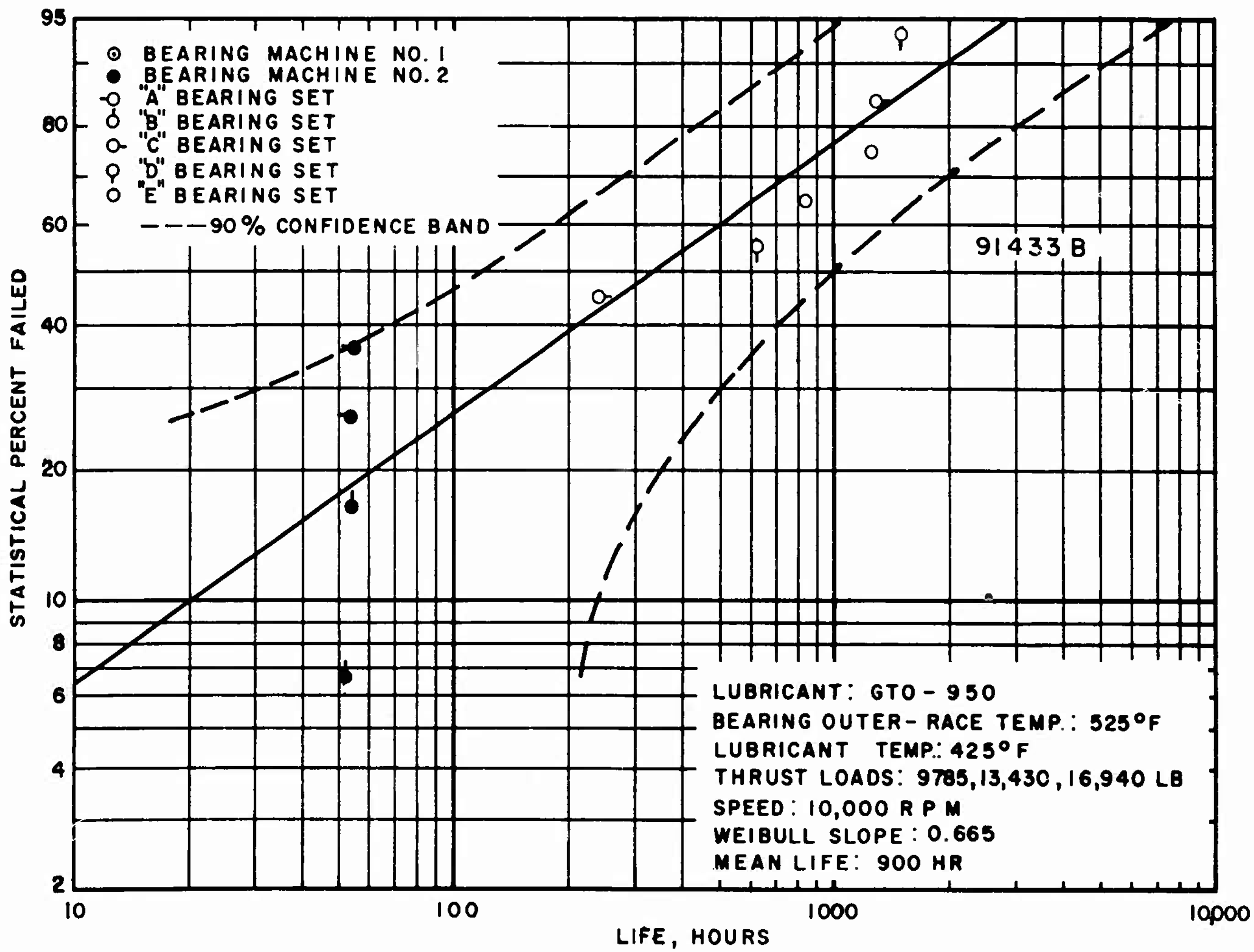


FIGURE 32. WEIBULL PLOT FOR STEP-LOAD 85-MM THRUST BEARING FATIGUE DATA

Figures 33 and 34 show a breakdown of the constant-load data in terms of machines. The curves are very similar having nearly equal slopes and life values.

The mean life (that life at which 50 percent of the bearings from a population may be expected to fail) for the tests on both machines is the same, namely 360 hours. This gives a mean life ratio of one and provides a "confidence number" of 50 percent. This means that there is only a 50 percent chance that the true mean life ratio is greater than unity.* Considering that both test samples were drawn from the same lot, this gives rather good assurance that at the particular load conditions used, the machines are identical.

For the step-load program, the four tests in the neighborhood of 52 hours in Figure 32 were made on machine No. 2. All other tests were made on machine No. 1. It is evident that if the data for the step-load program were plotted per machine, the result would be two quite dissimilar graphs, giving considerable confidence that the two machines are no longer identical. In an effort to resolve this difference in machines, the bearing loading procedure was examined. Each of these four bearings was tested without fatigue for 50 hours on machine No. 2. Then the load was increased about 50 percent and very quickly the bearings failed; by severe plastic deformation of the inner race as well as fatigue. Those bearings tested on machine No. 1 did not exhibit such sudden failure when the load was increased.

Examination of machine No. 2 revealed that the jet supplying oil to the test bearings was mislocated slightly so that it directed oil primarily onto the retainer instead of on the balls. Later experiments with No. 2 machine, using both a properly located and improperly located jet, definitely established that at a load of about 9800 lb, the jet location within the limits observed did not materially affect the bearing operation. At loads higher than this, heat generated by the bearing was greater than the cooling capacity of the misdirected oil stream, and this would almost certainly result in premature bearing failure. For this reason, the first four points of Figure 32 will be discarded and the remaining data plotted as Figure 35. It is this latter curve that will be compared with the constant-load curve of Figure 31.

To repeat, the hypothesis is first made that the results obtained from the step-load program are different from those obtained by the constant-load program, even though the samples for each program were from a single lot of near identical bearings. From the curves presented in Figures 31 and 35 mean lives of 360 and 1100 hours, respectively, were obtained. This mean

*See Appendix II for a brief outline of the statistical processes used in this work.

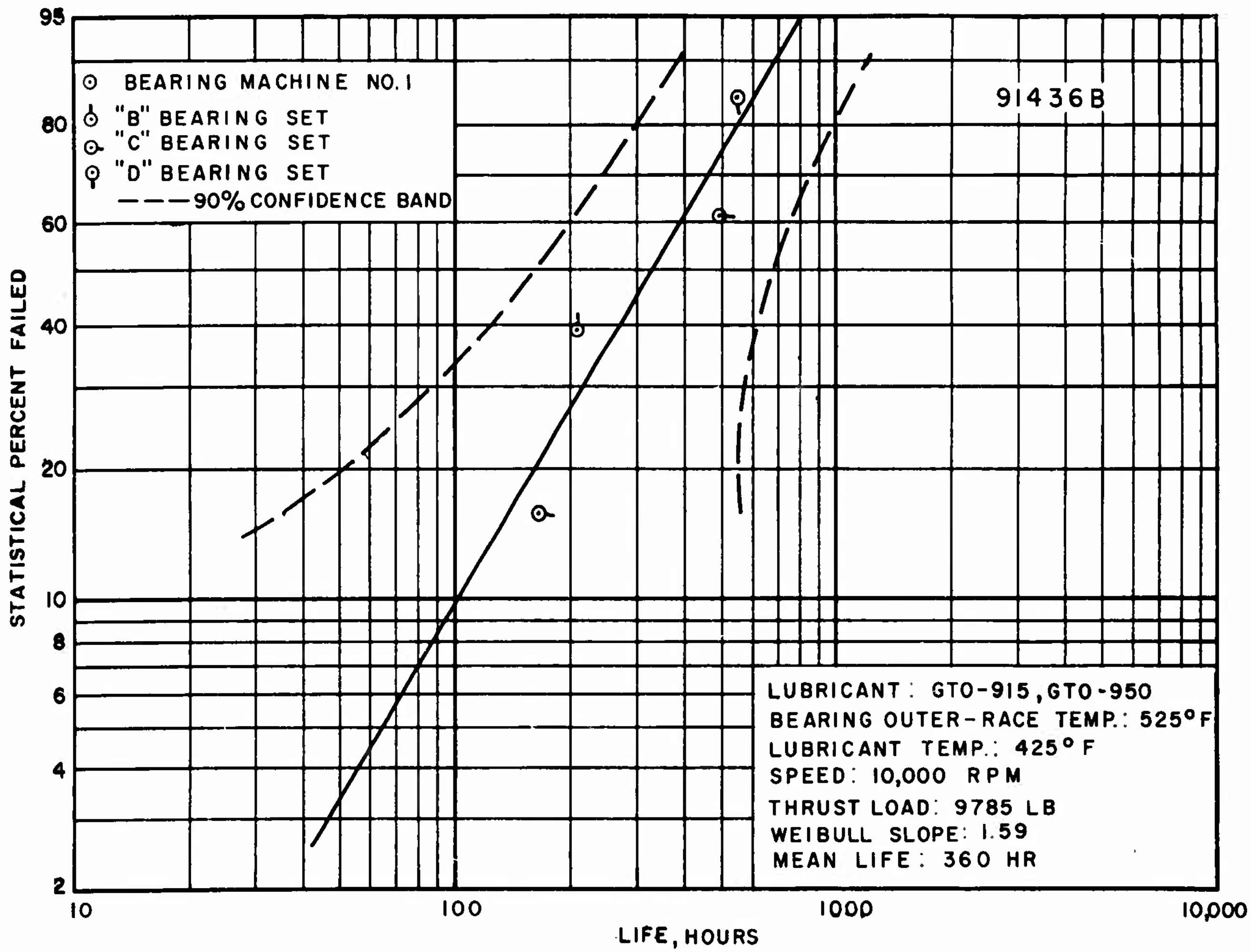


FIGURE 33. WEIBULL PLOT FOR CONSTANT-LOAD FATIGUE DATA OBTAINED ON 85-MM THRUST BEARING MACHINE NO. 1

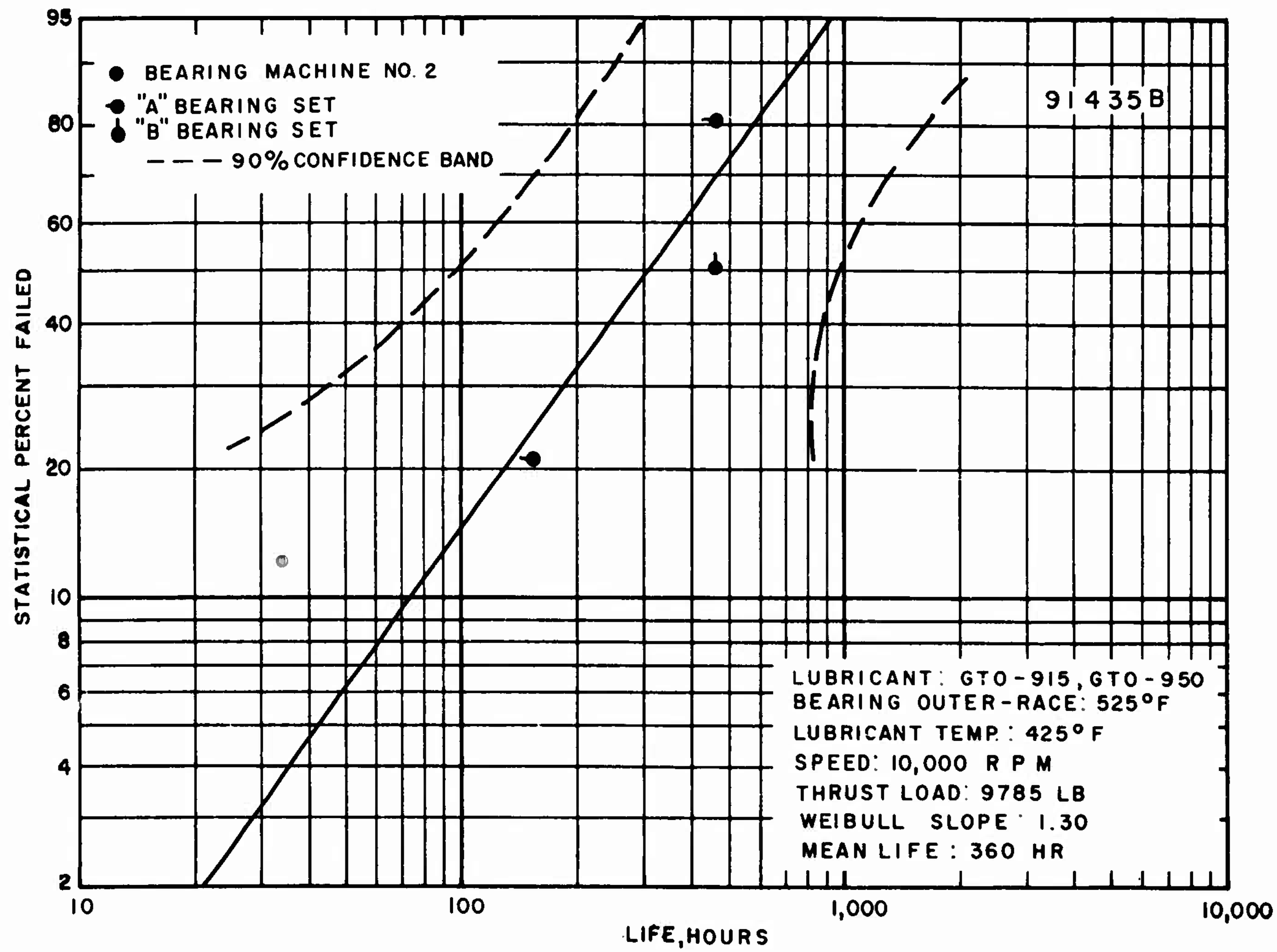


FIGURE 34. WEIBULL PLOT FOR CONSTANT-LOAD FATIGUE DATA OBTAINED ON 85-MM THRUST BEARING MACHINE NO. 2

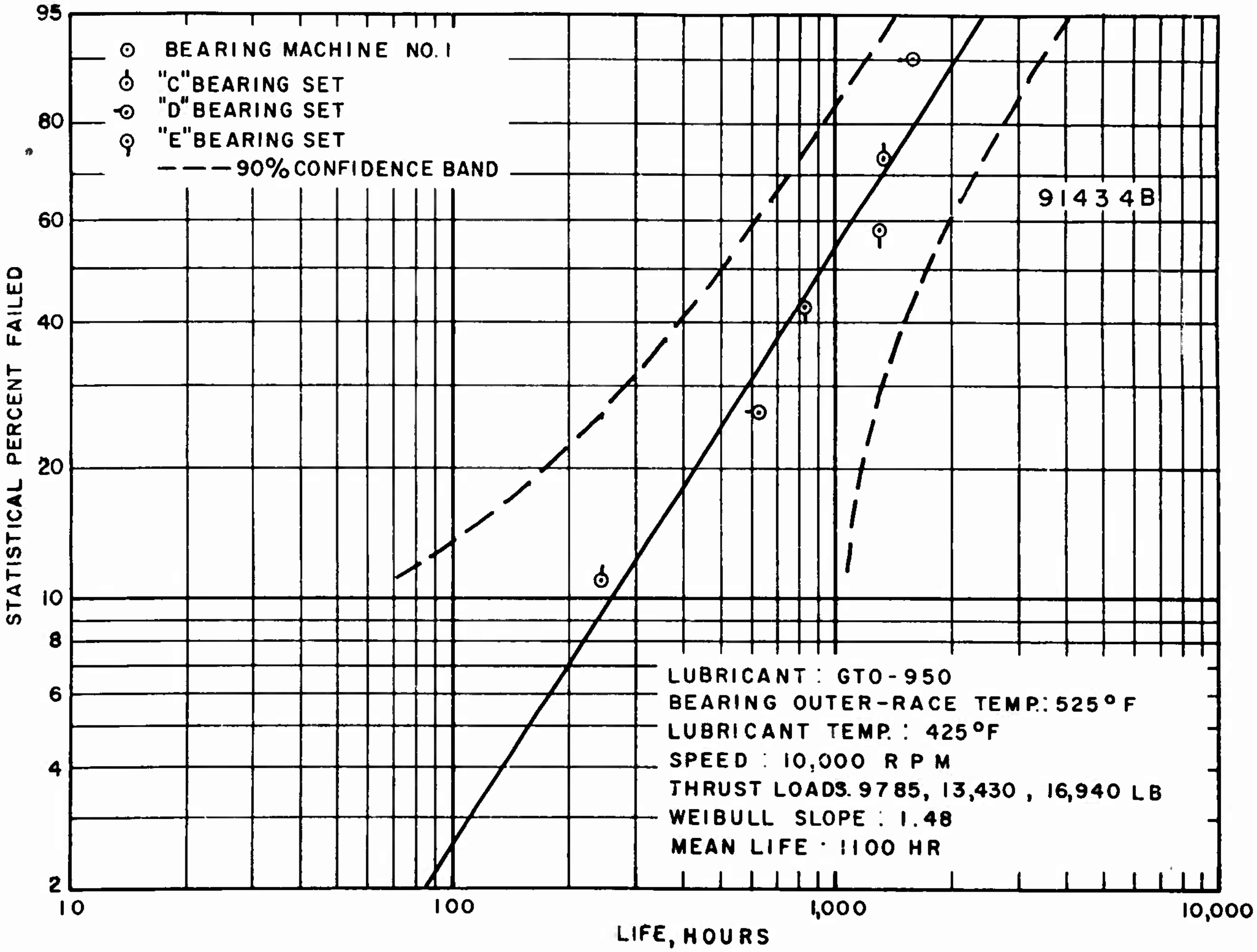


FIGURE 35. WEIBULL PLOT FOR STEP-LOAD 85-MM THRUST BEARING FATIGUE DATA (CORRECTED)

life ratio of 3.06 gives a confidence number in excess of 99 percent.* This implies that at least 99 times out of 100 the original hypothesis is true. At the ten percent failure level, with a ten percent life ratio of 1.85, the confidence number was about 71 percent. This means that with only ten percent of the program completed, it is evident that 71 times out of 100 the hypothesis is true.

Since the slope of the graphed line for any group of tests is only an estimate of the true population slope, it is of interest to know how accurate this estimate is. It can be determined that for a sample size of seven items, as in Figure 31, in 90 percent of all cases the slope will be within ± 45 percent of the observed slope of 1.73. For the six items in Figure 35, the slope will be within ± 47 percent of the observed slope of 1.48 ninety percent of the time. If the minimum slope for Figure 31 is contrasted to the maximum slope for Figure 35, a mean life ratio of 1.73 is obtained with a corresponding confidence number of 92 percent.

E. Development of the 20-mm Thrust Bearing Machine

The 20-mm thrust bearing program was initiated at the request of WADD to determine the operating capabilities, including the deterioration characteristics, of lubricants at high temperatures and speeds in a bearing test rig capable of simulating operating conditions and environments representative of typical flight vehicle power equipment designed for use in re-entry and high Mach flight vehicles.

1. Early Design of 20-mm Thrust Bearing Machine

An early version of this machine has been described in a previous report.(0.85) This machine was capable of operation with an oil temperature range of from 300 to 800°F, a speed range of 10,000 to 100,000 rpm and loads of 100 lb, although not all combinations of the above.

The preponderance of "failures" wherein the machine stopped without apparent physical damage or alteration in the test bearing led to an investigation, the result of which was that the temperature differential across the bearing may have eliminated the bearing internal clearance and caused the bearing to bind by thermal seizure.

This conclusion led to a design change in the test head which is discussed in the following paragraphs.

*See Appendix II.

2. Present Version of 20-mm Thrust Bearing Machine

In order to provide a test device which would not inject results into the test that were not functions of the lubricant alone, a modified test head was developed which provided a flexible test bearing mount. Additional controls and measuring apparatus were added to achieve fuller environmental control. A cross section of the modified 20-mm thrust bearing machine is shown in Figure 36. It will be noted that the auxiliary sump A and test bearing holder B are made in one piece. The thin cylindrical bearing holder is designed to accommodate sudden changes in the outside diameter of the bearing due to temperature changes within the bearing since a thin section bearing holder will tend to expand and contract with the bearing outer-race instead of constraining it. There are three large drain holes in the holder to provide ample drainage of the test oil thrown off the top of the test bearing C. This test oil and the test oil flowing through the bearing is drained from the housing D through two large drain lines F. Heating of the bearing is accomplished by means of a large band heater E, which surrounds the housing D.

Three support rods G for the housing act as retaining springs against the friction torque generated in the bearing. These support rods allow a slight angular motion of the housing, which is proportional to the friction torque. Motion is measured by means of a linear variable differential transformer (not shown).

The liquid barrier seal H includes a distributing ring for the seal oil and two leather washers which provide the sealing surfaces.

In order to obtain a measure of the shaft temperature, a small diameter (0.020 in.) bayonet thermocouple I extends through the auxiliary sump into a length of hypodermic tubing, which extends into a hole in the shaft. It is believed that shaft temperature data will provide valuable supplementary data for evaluation of bearing and lubricant performance.

Some tests made using this thermocouple have been successful, but its fragile nature necessitates going to a larger thermocouple.

F. Supporting 20-mm Bearing Test Equipment

1. Test Oil System

The test oil system has not been essentially altered from that used in the early version of the machine.[0.85] The 35-micron filter previously used has been discarded. Filter clogging was so prevalent that continued use was impractical. The intake on the test oil pump is fitted with a 200 mesh screen (0.0029-in. opening) which will stop those particles that

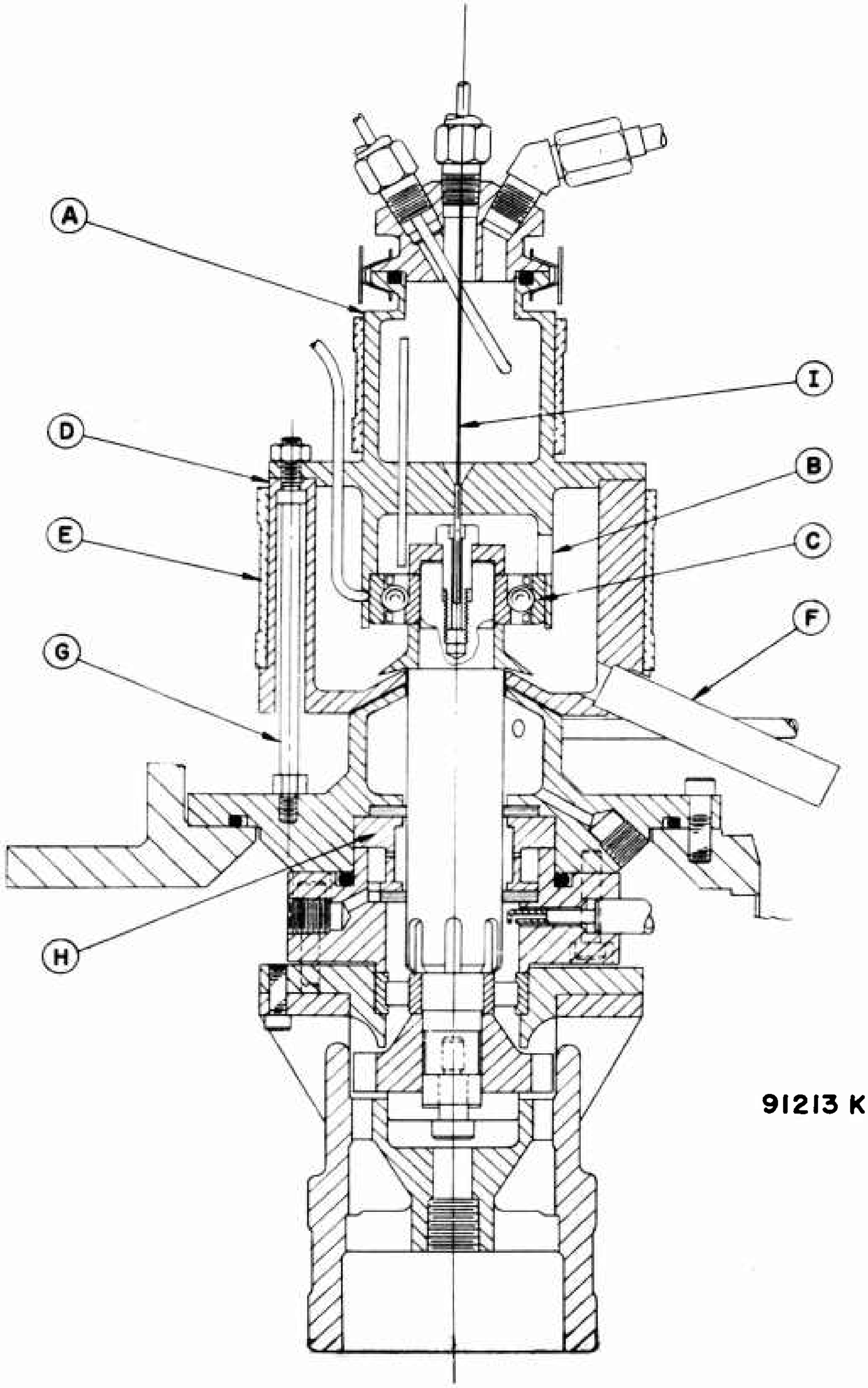


FIGURE 36. CROSS SECTION OF 20-MM THRUST BEARING MACHINE

might plug the jet (0.040-in. diameter). In addition, the jet intake is located near the top of the jet sump so that the larger particles which may be in the oil will tend to settle out before reaching the jet intake.

The main sump is heated with three instead of the original four band heaters, the uppermost heater having been removed. This was done so that when the oil level in the sump dropped a small amount the exposed sump wall would not be extremely hot. This "hot plate" effect resulted in excessive oil coking in this area during earlier tests.

2. Pneumatic Control System

This system has not been changed from that described in an earlier report.[0.85] It provides good regulation provided the upstream air in the surge tank is not disturbed.

3. Inert Gas System

This system has been altered slightly and is shown in Figure 37. The seal oil is fed by a gravity system instead of a pump and bypass. This is designed to reduce the oil pressure on the seals. If the seals do not leak excessively then the flow rate is very small. If they begin to leak, flow increases and the oil either is swept out through the turbine exhaust or collected by the gravity drain. The oil from either source may be put back into the seal oil sump periodically.

A manometer has been installed to monitor closely the chamber pressure so as always to maintain it positive. A positive pressure of approximately 1 in. Hg is usually used.

4. Miscellaneous Controls

Some additions to the overall rig have been made in the interest of better control and observation. These are electrical in nature. A wattmeter shows the power used in heating the bearing. Voltmeters provide a measure of the bearing heater, jet sump heater, and main sump heater voltages. Previously these values were "measured" by settings on a variable transformer, the proper setting being determined experimentally.

A small auxiliary sump has been attached to the test chamber in order to add test oil lost by evaporation and withdrawn for viscosity and neutralization number determinations. The use of this sump eliminates directly opening the test chamber during a run.

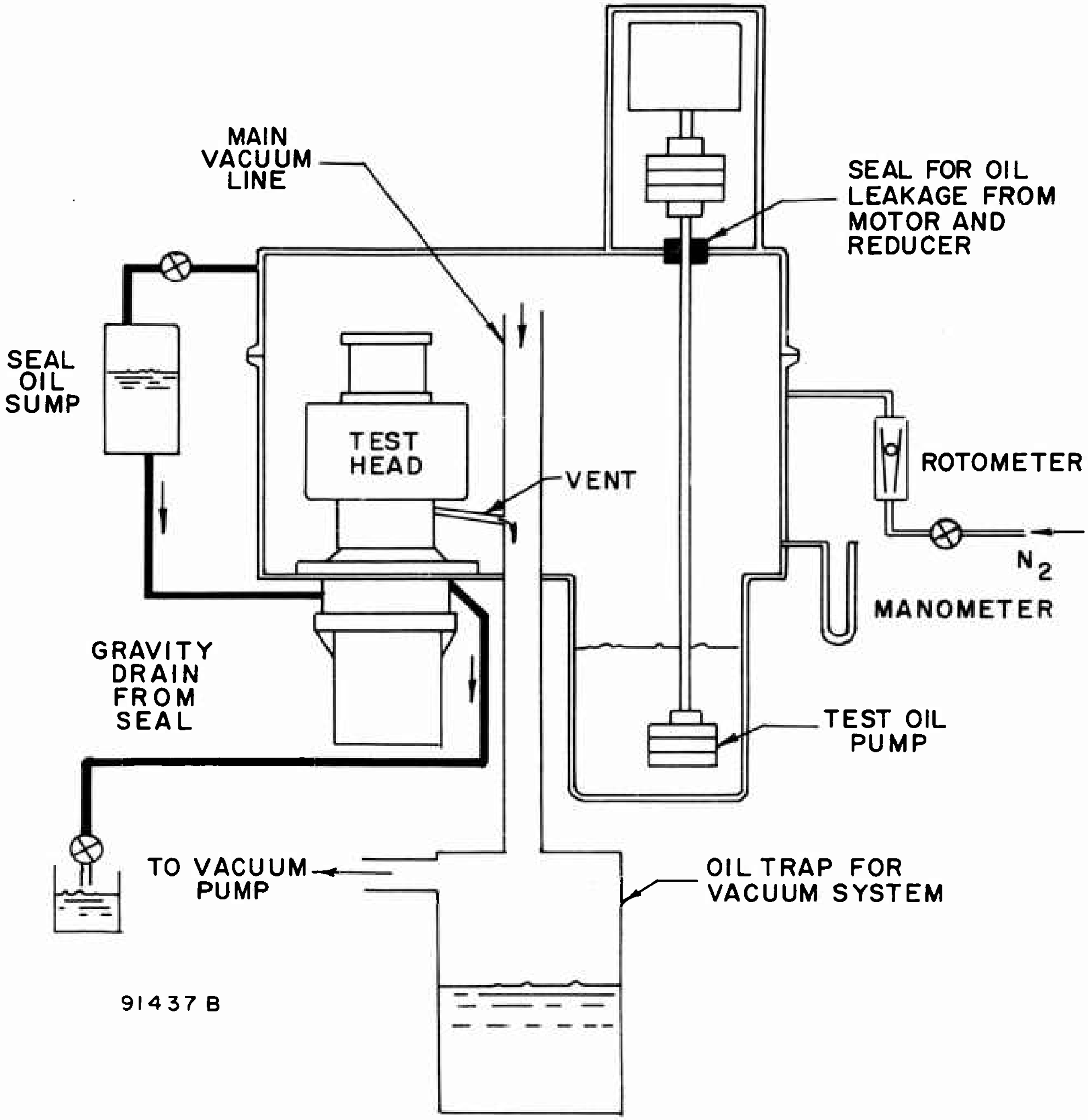


FIGURE 37. SCHEMATIC DIAGRAM OF VACUUM AND INERT GAS SYSTEM

G. High-Temperature 20-mm Test Bearings

The test bearings are angular-contact ball bearings designated as AAMM204WO MMR, and made by Fafnir Bearing Company to ABEC-7 tolerances. These bearings were obtained from a single heat of consumable electrode M-50 steel. The cage is made of preoxidized S-monel metal, and is designed to ride on the outer race of the bearing. The major dimensions are as follows:

Inside diameter, mm	20
Outside diameter, mm	47
Bearing width, mm	14
Ball complement	10
Ball diameter, in.	5/16
Contact angle, degree	20

H. Lubrication Deterioration Tests

The material presented in this section represents results obtained using the early version of the 20-mm thrust bearing machine. Twenty-three tests were conducted on five lubricants. All of these tests were run at 50,000 rpm, a nominal thrust load of 100 lb, and a bearing outer-race temperature of 700°F. The test oil-in temperature and the sump temperature were generally maintained equal, and controlled at either 500, 600 or 700°F. The test oil flow for 22 of the 23 tests was maintained at 50 ml/min. The test oil flow was maintained at 100 ml/min for only one test. To minimize lubricant deterioration, the system was blanketed with a nitrogen atmosphere. Test oil samples were taken every 5 hours for viscosity and neutralization number determinations. The test oil consumption was also checked regularly, but generally no make-up oil was added. The test duration was to be either 25 hours, or until a lubricant or bearing failure occurred.

Table 25 has been prepared to give a summary of the performance of five lubricants evaluated in the 20-mm thrust bearing machine. These data were taken from the summary tables for each lubricant given in Tables 46 to 55 in Appendix III. In Table 25, as well as in the tables in the Appendix, the tests which failed to reach 25 hours are classified into three primary modes of failure--oil, bearing and rig. A failure is attributed to the oil when deterioration is such that drain lines completely plug and improper lubrication results; a failure is attributed to the bearing when seizure occurs while the bearing is still being adequately lubricated (such as due to thermoelastic seizure); rig failures are due to malfunction of mechanical or electrical equipment.

There are two summary tables for each lubricant given in Appendix III (Tables 46 through 55). The first of these tables gives the test conditions

TABLE 25. SUMMARY OF PERFORMANCE OF LUBRICANTS EVALUATED IN 20-MM THRUST BEARING MACHINE

Oil Code	No. of Tests	Bearing Outer-race Temp., F	Test Oil-in Temp., °F	Test Oil Flow, ml/min	No. of Completed 25-Hr Tests	No. of Failures		
						Oil	Bearing	Rig
C-1003	3	700	500	50	2	0	0	1
	5	700	600	50	0	0	4	1
	1	700	600	100	0	1	0	0
Ref. "B"	3	700	500	50	1	2	0	0
GTO-915	1	700	500	50	0	0	0	1
LRO-8	4	700	500	50	0	1	2	1
	2	700	600	50	0	2	0	0
LRO-12	1	700	500	50	1	0	0	0
	2	700	600	50	0	0	1	1
	1	700	700	50	1	0	0	0

and a description of the test results. The second of the summary tables for each lubricant gives the viscosity and neutralization number data.

Referring to Table 25, it will be noted that there were a large number of bearing and rig failures which could not be properly ascribed to lubricant performance. For this reason, the results obtained to date give no clear-cut indication of the performance capability of the lubricants. It has been determined that a large number of the bearing failures were due to a thermoelastic squeeze effect, such that under certain operating conditions all clearance in the test bearing was lost and thus bearing seizure resulted, (Ref. 11.12).

I. Experimental Work Using the Modified Head, 20-mm Thrust Bearing Machine

Tests using this newer version have remained in the exploratory stage in order to fully evaluate capabilities and characteristics. Thermal seizure does appear to have been eliminated. However, some difficulty has been experienced in temperature attainment and control, particularly of the bearing and jet sump. This is currently being worked on.

The leather seals in the illustration (Fig. 36) have not proved very successful. They tend to bind and char, scoring the shaft. However, the necessity of seals has been demonstrated by the relative cleanliness of the lubricant tested in this exploratory work (a light weight mineral oil) when using seals as contrasted to the excessive carbonaceous deposits and test oil volume loss when operating without seals. Some analyses by gas chromatography of the oxygen content in the test chamber indicate an oxygen content of about one percent using seals and about eight percent with no seals. The best seals to date have been ordinary leather lip seals with the garter spring removed. These seals are flooded with oil during the run. It would be desirable to have a more flexible lip than the commercial seals possess. Since operation under nitrogen utilizes a small positive chamber pressure which tends to keep out air except that small amount which diffuses into the nitrogen through the seal region, the seals need be effective only at the start of the test. This is when the chamber must be evacuated and the nitrogen blanket established. Machine operation under the simulated space condition of vacuum cannot be made using this type of seal. Positive contact seals must be utilized and space for such is provided in the test head when such operation becomes necessary.

J. Conclusions

In the light of the relatively small number of data points available for the statistical analysis of the results from the 85-mm bearing fatigue program, it

can only be concluded that although the bearings tested were from the same population, the methods of testing did not produce similar results. No definite reason has been established at this time for this difference. Since the "cube rule" used for obtaining equivalent hours at a particular load has been established from many industrial tests, it can at best represent an "average" only. That is to say that particular lots of bearings may exhibit quite different results from this "average."

In the interest of further comparison it is recommended that future test programs be conducted using the constant-load procedure with either a different material from M-50 steel (such as 52100 steel), or else a larger load than the 9785 lb currently used. If the step-load procedure is still deemed desirable, it is recommended that much larger samples be tested than are reported herein. This would be, needless to say, very expensive.

While the 20-mm thrust bearing machine, as it appears to date, is a useful tool for oil evaluation tests at moderate conditions, it requires further refinement to properly and confidently extend its usefulness to severe conditions. One area needing more work is that of directing sufficient heat to the test bearing. Of necessity, the test bearing must have a small volume housing surrounding it which possesses flexibility. These conditions are not compatible with good heat transfer from the bearing heater to the bearing. Current methods of correcting this show much promise.

Seals for atmospheric operation with a nitrogen blanket will require additional work. Leather shows the most promise as of now, but its flexibility must be increased.

As soon as the rig is standardized and an operating procedure developed that is sufficiently flexible to cope with the varying characteristics of the lubricants, it is contemplated that repeatability tests will be made on a number of lubricants. Upon the successful completion of these, a formal program of lubricant evaluation will be initiated.

IV. LUBRICANT OXIDATION

A. General Remarks

This phase of the program has been concerned with evaluating the oxidation and corrosive tendencies of advanced lubricant formulations with a lubricant oxidation test apparatus in accordance with Celanese Chemical Company specifications, and determining the repeatability and reproducibility of the test.

The Celanese oxidation test procedure was developed by the Celanese Chemical Company in an effort to provide a method of predicting the oxidative performance of jet engine lubricants covered by Specification MIL-L-9236B.

In the Celanese test procedure, a sample of test fluid is maintained at a controlled temperature of 425°F for a period of 45 hours in the presence of metal specimens, and a controlled air flow is maintained through the sample. The viscosity, neutralization number and the overhead losses of the sample are determined at specified intervals throughout the test period. At the end of the test, the amount of corrosive attack on the metal specimens by the oil sample, the amount of acidic material in the condensed overhead losses, and the final viscosity and neutralization number of the sample are determined.

During the present contract period, the modification of an oil bath available at SwRI and the installation of the accessory equipment were completed, and investigations were conducted to determine the degree of control of certain test parameters that can be maintained with equipment currently available at SwRI. These test parameters consisted of the uniformity of temperature in different regions of the oil bath, the variation of oil bath temperature from the controlled temperature over a period of time, and the variation of air flow with respect to time when controlling at the specified air flow rate. It was established that the control of these test variables, when using the equipment available at SwRI, is adequate to meet the Celanese specifications.

In addition to the preliminary investigations, oxidation tests have been conducted on nine different test fluids, namely GTO-939, 0-58-24, 0-59-26, 0-60-11, 0-60-12, 0-60-13, 0-60-23, 0-60-26, and 0-60-27. Based upon the results and experiences obtained in these oxidation tests, it appears that the Celanese oxidation test apparatus and procedure have a promising prospect of yielding a reasonable degree of repeatability and reproducibility. However, a definite conclusion cannot be made until more data and experience are acquired.

B. Celanese Oxidation Test Apparatus

During the present contract period, the construction of the oxidation test apparatus was completed to conform with the specifications provided by the Celanese Chemical Company. All glassware directly related to the test cells was obtained to the exact specifications. In order to reduce the cost of capital equipment to the project, the other necessary items, such as the oil bath and the air flowmeters, were obtained from supplies available at SwRI. The various items were thoroughly checked to assure that their performance would satisfy the specified requirements. Figure 38 is a photograph of the oxidation test apparatus as installed.

1. Test Bath

An oil bath available at SwRI was modified to meet the specified requirements. The modifications of the oil bath included the fabrication of a top and bottom rack to hold the test cells in position, the addition of a Model L "Lightnin" stirrer to circulate the bath medium, and the addition of a thermocouple in conjunction with a temperature recorder to provide a record of the bath temperature throughout the test.

Grade 1100 engine oil was used as the bath medium. The selection of this oil was based upon the satisfactory performance of this oil as bath medium up to 500°F from previous experience at SwRI.

The temperature control of the oil bath is provided by four 450-watt immersion heaters, one of which is controlled by an adjustable thermoswitch. Investigations have been made to determine the temperature variation of the bath medium at the four extreme locations of the test cells. These results are summarized in Table 26. The test temperature specified by Celanese allows for a maximum spread of 4°F; therefore, it will be noted from Table 26 that the oil bath available at SwRI is capable of easily meeting this requirement.

2. Air Control System

A schematic drawing of the air flow-control system is presented in Figure 39. A precision air pressure regulator provides a constant air pressure to the individual control valves from the shop air line. These control valves are needle valves with fine adjusting screws, which allow the operator to maintain a correct amount of air flow over a long period of time. The air passes through a common drying column, containing a calcium sulfate (indicating) drier, and a manifold before reaching the individual test cell control valves and flowmeters. Each of the six air flowmeters were calibrated by

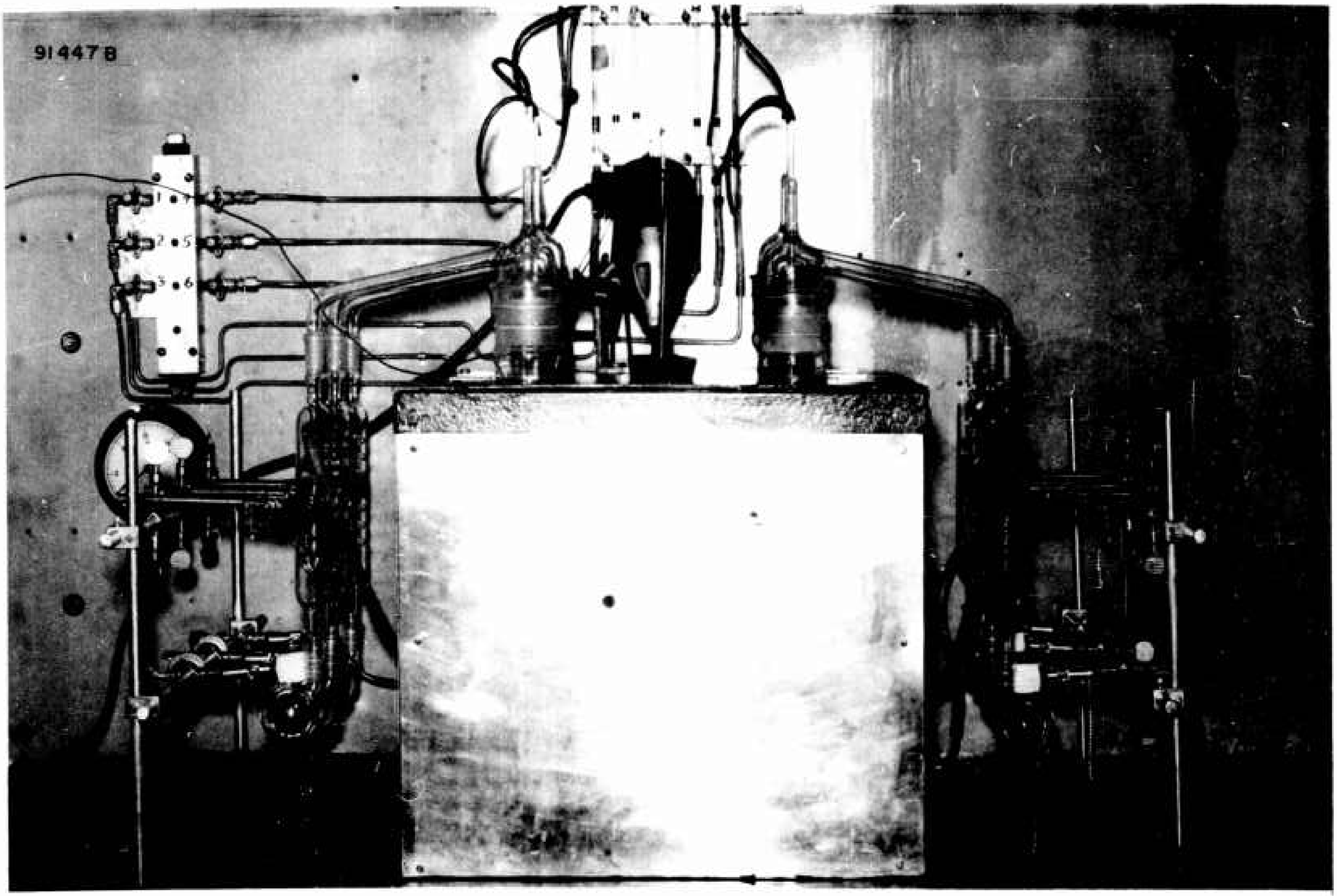


FIGURE 38. PHOTOGRAPH OF CELANESE OXIDATION TEST APPARATUS

TABLE 26. MAXIMUM TEMPERATURE VARIATION FOR THE OIL BATH MODIFIED FOR USE WITH THE CELANESE LUBRICANT OXIDATION TEST APPARATUS

Oil Bath Temperature, °F	Maximum Variation Within the Bath, °F	Maximum Variation Over a 1-Hour Period, °F
300	1	2
400	0	2
450	0	1

Bath medium temperatures were measured at the four extreme locations of the test cells.

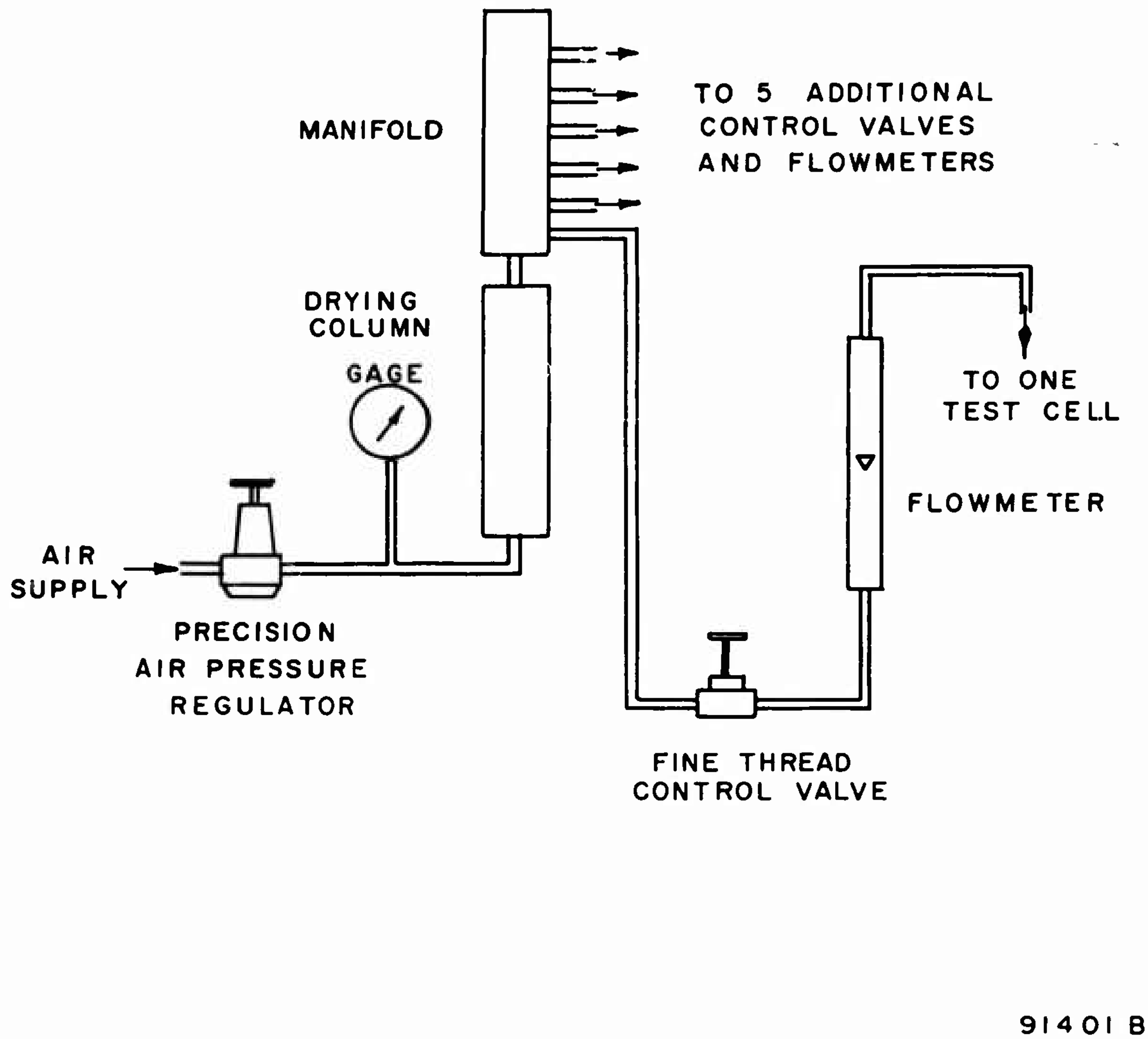


FIGURE 39. AIR FLOW-CONTROL SYSTEM FOR CELANESE OXIDATION TEST APPARATUS

means of a wet-test meter to assure accurate measurement of an air-flow rate of 96 ± 2 liters/hr, which was specified for each test cell.

3. Metal Test Specimens

In the Celanese test procedure, metal test specimens conforming to the following specifications are used:

Metal	Specification
Copper	QQ-C-576
Steel	QQ-S-636, cold-rolled, bright finish
Aluminum Alloy	QQ-A-355, Temper T-3 or T-4
Titanium Alloy	MIL-T-9046
Silver	Electrolytic grade

Figure 40 presents the dimensions of the metal test specimens and the recommended configuration of the specimen group.

4. Glassware

The glassware used in the Celanese oxidation test is as follows (specifications taken from Celanese Chemical Company test method)[11, 13]:

(1) Test cell and head - See Figure 41. Because of the nature of the test, reversing the joints, that is, having male joint on the sample tube and female joint on the head is not recommended.

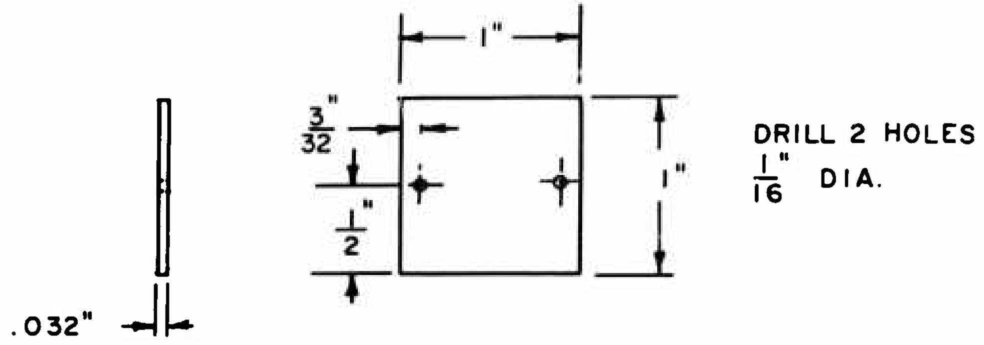
(2) Air inlet tube - Standard 5-mm glass tubing, approximately 610-mm in length.

(3) Condensers - Graham, ₮ 19/38 joints at both ends, approximately 200-mm in length.

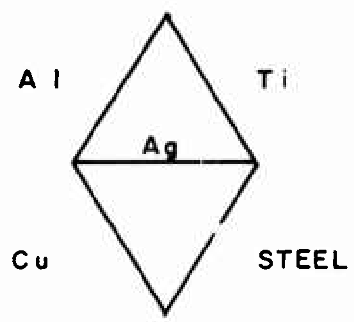
(4) Condensate flask - 100 ml round bottom two-neck flask, both necks ₮ 19/38 joints.

(5) Air inlet tube connector - Two-inch piece of 5-mm glass tubing fitted with a 3-in. piece of suitable rubber tubing.

Six complete sets of the above glassware were used by SwRI during each test period. This requirement may vary among laboratories depending upon the size of the heating bath used.



TEST SPECIMEN



TEST SPECIMEN CONFIGURATION

91402 B

FIGURE 40. METAL TEST SPECIMEN AND TEST SPECIMEN CONFIGURATION USED IN CELANESE OXIDATION TEST PROCEDURE

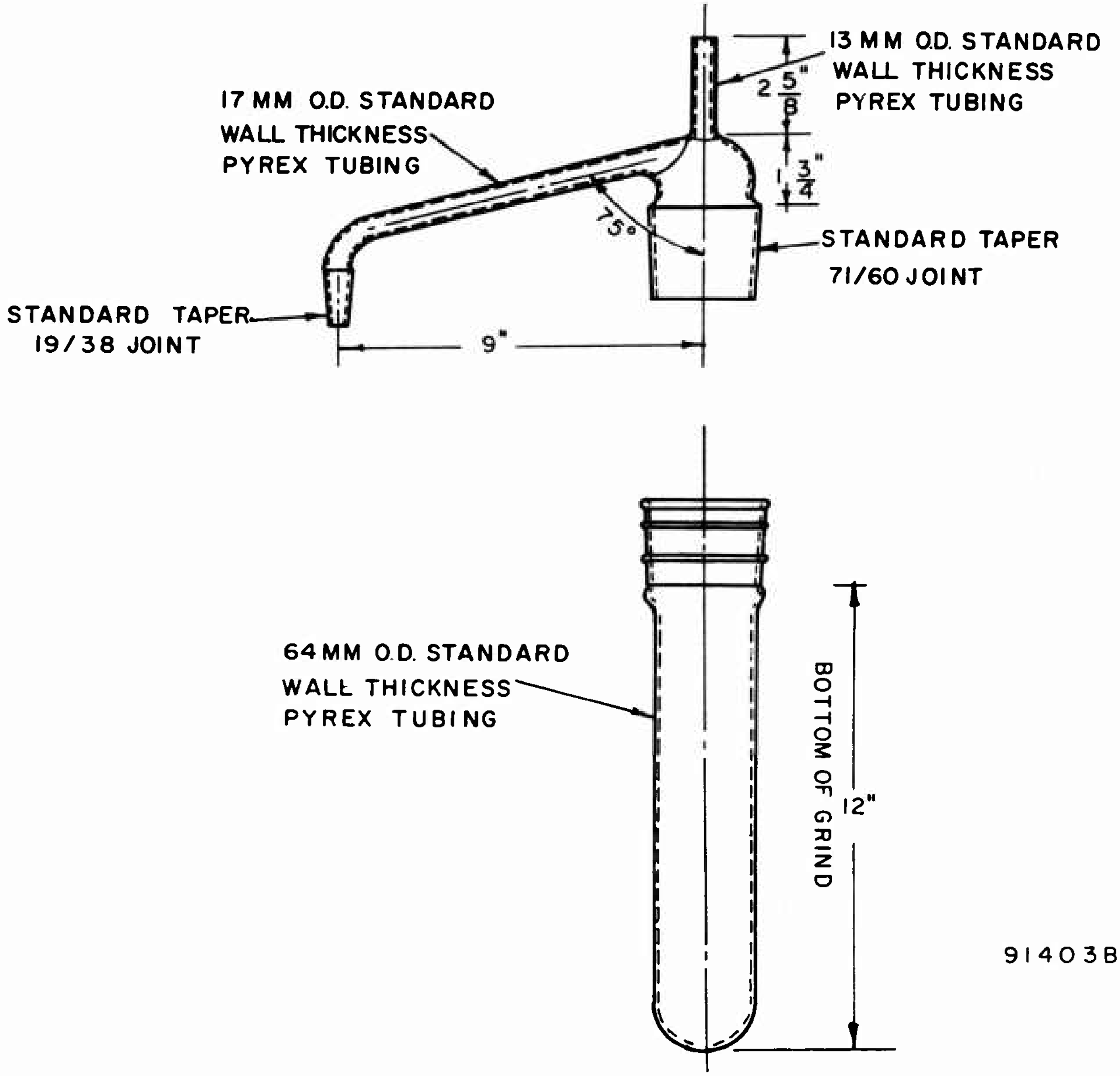


FIGURE 41. TEST CELL AND HEAD FOR CELANESE OXIDATION TEST APPARATUS

C. Celanese Oxidation Test Procedure

The bath temperature is maintained at 425 ± 2°F throughout the test. The metal specimens are first polished, weighed to the nearest 0.1 mg, and then tied in the recommended configuration with clean nichrome wire. While, or before, the metal specimens are weighed and tied, the clean, dry test cell is filled with 250 ml of the test fluid. The air delivery tube is then inserted through the head and held in place by means of a tight-fitting cork. The head is given a very thin coating of silicone grease around the upper joint area; the metal specimen group is gently inserted in the test cell and the unit assembled so that the air delivery tube passes through the metal specimen configuration on either side of the diagonal silver specimen. The delivery tube is then lifted 1/8 in. from the bottom of the test cell. The entire assembly is then weighed to the nearest gram.

The assembled oxidation cells are gently lowered into the bath and the head arms are fitted securely into the condensers to which the condensate flasks are attached. The circulation of cooling water through the condensers is started and the air supply is connected to the air delivery tube by means of rubber tubing. After a 15-minute warm-up period, the air flow (96 liters/hr) is started. At the end of 5 hr ± 5 min, the air flow is disconnected and the test cells are removed from the bath, wiped clean of oil, and placed in a tube holder. The individual test cell assemblies are weighed to the nearest gram, and the change in weight is determined. At the end of each 5-hr test period, overhead losses are made up by adding fresh test fluid. After each 5-hr period following the initial 10 test hours, a 20-ml sample is taken from each test cell. This sample weight is not made up by fresh test fluid. A neutralization number and viscosity test are conducted on each sample taken from the test cells. At the end of the test, the metal specimens are removed and cleaned with warm acetone and chloroform. Each metal specimen is then weighed to the nearest 0.1 mg to determine the weight change in milligrams per square centimeter of surface area. The acidity of the condensate from the overhead losses is also determined at the end of the test.

The first test procedure received from the Celanese Chemical Company recommended a test duration of 35 hours; recently, this recommendation has been changed to 45 hours. However, SwRI has operated the test for a period of 50 hours for all but the initial tests on one lubricant.

A minor change was made in the Celanese procedure in connection with the removal of the 20-ml sample and the addition of fresh oil. The samples were drawn from each test cell by attaching a piece of rubber tubing to the air delivery tube and drawing the oil out with a pipette and a rubber suction bulb. This change was made because some oils became very dark after a short period of time in the oil bath and it was sometimes very difficult,

after the head was removed and the oil samples drawn out, to replace the air delivery tube through the metal specimen group in the recommended manner. The fresh oil was added to the test cells through the air delivery tube by means of a syringe.

In regard to the cleaning of test cells and heads at the end of the test, a preliminary cleaning with hot caustic soda solution has been used instead of the recommended acetone flush because of the nature of the deposits left by some test oils. After initially cleaning the test cells with the hot caustic soda solution, the remaining cleaning procedures suggested by Celanese were followed. These procedures are briefly outlined as follows: The test cells are filled approximately 2/3 full with a concentrated HNO_3 - concentrated H_2SO_4 mixture (1:10 by volume) until all deposits are removed; then the test cells are flushed with tap water and soaked in chromic acid until clean. After that, the test cells are flushed with tap water, then distilled water, and allowed to dry in an oven. After the heads are cleaned with hot caustic soda solution and flushed with tap water, they are soaked in chromic acid until clean, then flushed with tap water and distilled water, and allowed to dry in the oven.

With respect to the polishing of the metal specimens, the four edges and two flat surfaces were given an initial polish with 240 grit carborundum paper. It is not recommended to use the same carborundum paper for different types of metal. Upon completion of this preliminary polish, the metal specimens were then polished with 400 grit carborundum paper. It is suggested that the operator should wear a pair of clean cotton gloves in this final polish to avoid contamination of the metal specimens, and only longitudinal strokes are recommended. After a clean and blemish-free metal surface was obtained, the specimen was vigorously swabbed with clean iso-octane and reagent grade acetone to remove the remaining metal particles, and stored in clean iso-octane or precipitation naphtha as specified.

D. Oxidation Test Results

A program has been in progress to determine the oxidative and corrosive tendencies of certain lubricants selected by WADD in an effort to evaluate the Celanese test procedure as a test method for predicting bearing rig and engine life performance of jet engine lubricants.

During this contract period, oxidation tests were made on nine different lubricants (GTO-939, 0-58-24, 0-59-26, 0-60-11, 0-60-12, 0-60-13, 0-60-23, 0-60-26, and 0-60-27 oils) using the Celanese oxidation test procedure outlined in the preceding paragraphs. A summary of the average test results obtained is presented in Table 27. Graphs of the average viscosities and neutralization numbers versus test time for the nine different lubricants are presented in Figures 42 and 43 respectively. The individual test

TABLE 27. SUMMARY OF AVERAGE OXIDATION TEST RESULTS OBTAINED FOR NINE DIFFERENT LUBRICANTS USING THE CELANESE OXIDATION TEST PROCEDURE

Oil Code	Tests	Test Time, hours 0	15	20	25	30	35	40	45	50	Total Overhead Acidity, mg KOH/g	Total Make-up, g
GTO-939	Viscosity, cs at 100°F	15.06	17.24	18.26	20.56	25.11	28.71	34.77	38.23	40.62	22.41	183.0
	Neut. No., mg KOH/g	0.04	0.50	0.94	2.58	4.13	5.65	6.70	4.92	4.90		
	Make-up, g		16.3	16.8	20.3	22.0	15.8	18.8	16.8	13.8		
0-58-24	Viscosity, cs at 100°F	34.65	56.41	65.93	78.61	99.50	127.02	140.43	160.32	194.71	26.44	172.5
	Neut. No., mg KOH/g	0.14	12.13	8.78	7.06	5.25	5.45	4.55	5.76	6.04		
	Make-up, g		24.5	22.7	20.2	15.0	13.8	15.0	9.8	9.3		
0-59-26	Viscosity, cs at 100°F	18.67	20.18	20.50	23.01	28.16	37.28	47.18	55.36	62.77	40.26	86.3
	Neut. No., mg KOH/g	0.09	0.18	0.26	1.32	3.83	5.83	6.63	7.58	8.08		
	Make-up, g		5.8	6.3	6.5	9.2	12.2	12.3	11.3	6.2		
0-60-11[a]	Viscosity, cs at 100°F	21.24	18.83	18.74	18.98	18.47	19.56	19.75	-	-	11.62	123.0
	Neut. No., mg KOH/g	38.54	5.82	5.84	5.86	5.53	5.26	5.10	-	-		
	Make-up, g		16.3	15.0	15.0	20.5	11.0	11.0	-	-		
0-60-12[b] (D-1074)	Viscosity, cs at 100°F	16.14	17.71	18.05	18.07	18.19	18.58	18.91	18.96	19.25	4.97	105.0
	Neut. No., mg KOH/g	0.13	0.41	0.51	0.61	0.61	0.71	0.73	0.77	0.77		
	Make-up, g		7.8	11.0	14.0	10.5	6.2	11.2	10.2	8.7		
0-60-12[c] (D-1087)	Viscosity, cs at 100°F	16.12	17.57	17.65	17.95	18.11	18.45	21.37	18.82	19.13	3.81	102.3
	Neut. No., mg KOH/g	0.03	0.41	0.38	0.39	0.45	0.47	0.47	0.48	0.53		
	Make-up, g		9.5	11.7	10.5	9.8	9.2	10.7	9.5	9.2		
0-60-13	Viscosity, cs at 100°F	25.67	30.03	30.94	33.36	33.05	35.62	43.88	52.73	62.28	28.90	63.5
	Neut. No., mg KOH/g	0.07	0.74	0.85	0.99	1.26	2.47	4.25	5.59	6.59		
	Make-up, g		5.3	5.7	6.6	4.7	5.3	8.0	6.3	6.8		
0-60-23[d]	Viscosity, cs at 100°F	16.02	17.38	17.55	17.68	17.77	18.06	-	-	-	3.72	74.8
	Neut. No., mg KOH/g	0.05	0.30	0.27	0.31	0.35	0.51	-	-	-		
	Make-up, g		13.1	10.7	11.3	9.3	9.6	-	-	-		
0-60-23	Viscosity, cs at 100°F	16.02	17.30	17.45	17.63	17.86	17.96	18.11	18.23	18.49	4.03	99.1
	Neut. no., mg KOH/g	0.05	0.37	0.44	0.42	0.45	0.54	0.63	0.54	0.68		
	Make-up, g		11.4	11.0	10.1	10.3	8.9	8.5	10.1	11.5		
0-60-26[e]	Viscosity, cs at 100°F	15.04	17.35	18.37	21.04	25.73	32.07	37.98	41.72	44.78	18.22	187.8
	Neut. No., mg KOH/g	0.04	0.52	1.04	2.41	4.00	5.28	5.93	5.74	5.24		
	Make-up, g		16.8	21.5	17.3	20.3	20.0	20.3	18.0	13.5		
0-60-27[e]	Viscosity, cs at 100°F	15.00	17.42	18.64	22.12	27.31	32.19	38.23	43.45	47.43	23.63	188.14
	Neut. No., mg KOH/g	0.07	0.52	1.18	2.71	3.95	6.23	5.35	7.36	6.45		
	Make-up, g		18.0	18.9	20.3	20.4	20.3	18.8	17.9	16.7		

Average test results obtained from individual determinations listed in the appendix.

(a) Tests discontinued after 40 hr due to clogged condensers.

(b) Oil received from manufacturer.

(c) Oil received from WADD.

(d) Tests discontinued after 35 hr in accordance with first test procedure received from Celanese Chemical Company.

(e) A different batch of GTO-939.

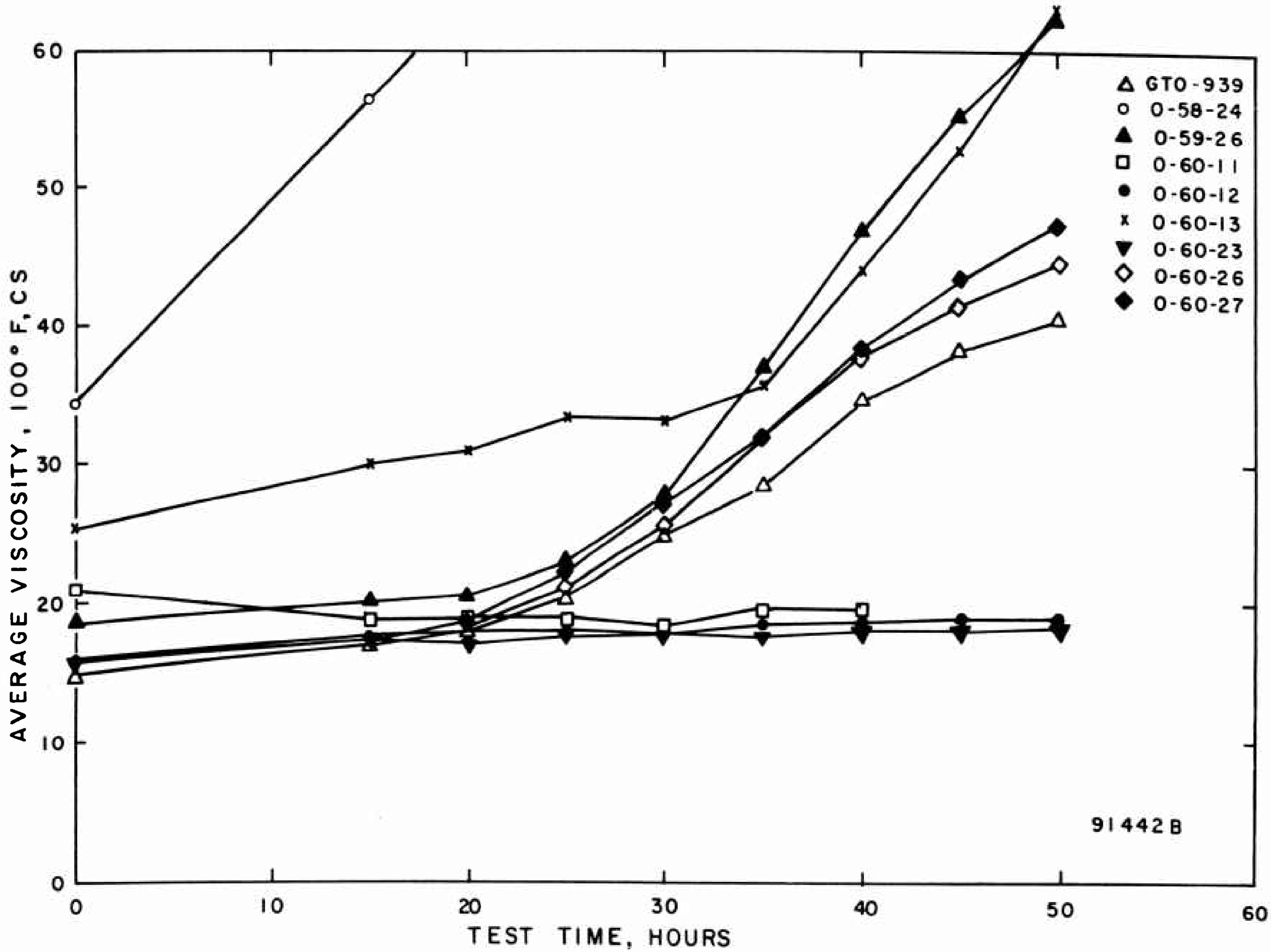


FIGURE 42. AVERAGE VISCOSITIES FOR NINE DIFFERENT LUBRICANTS VERSUS TEST TIME

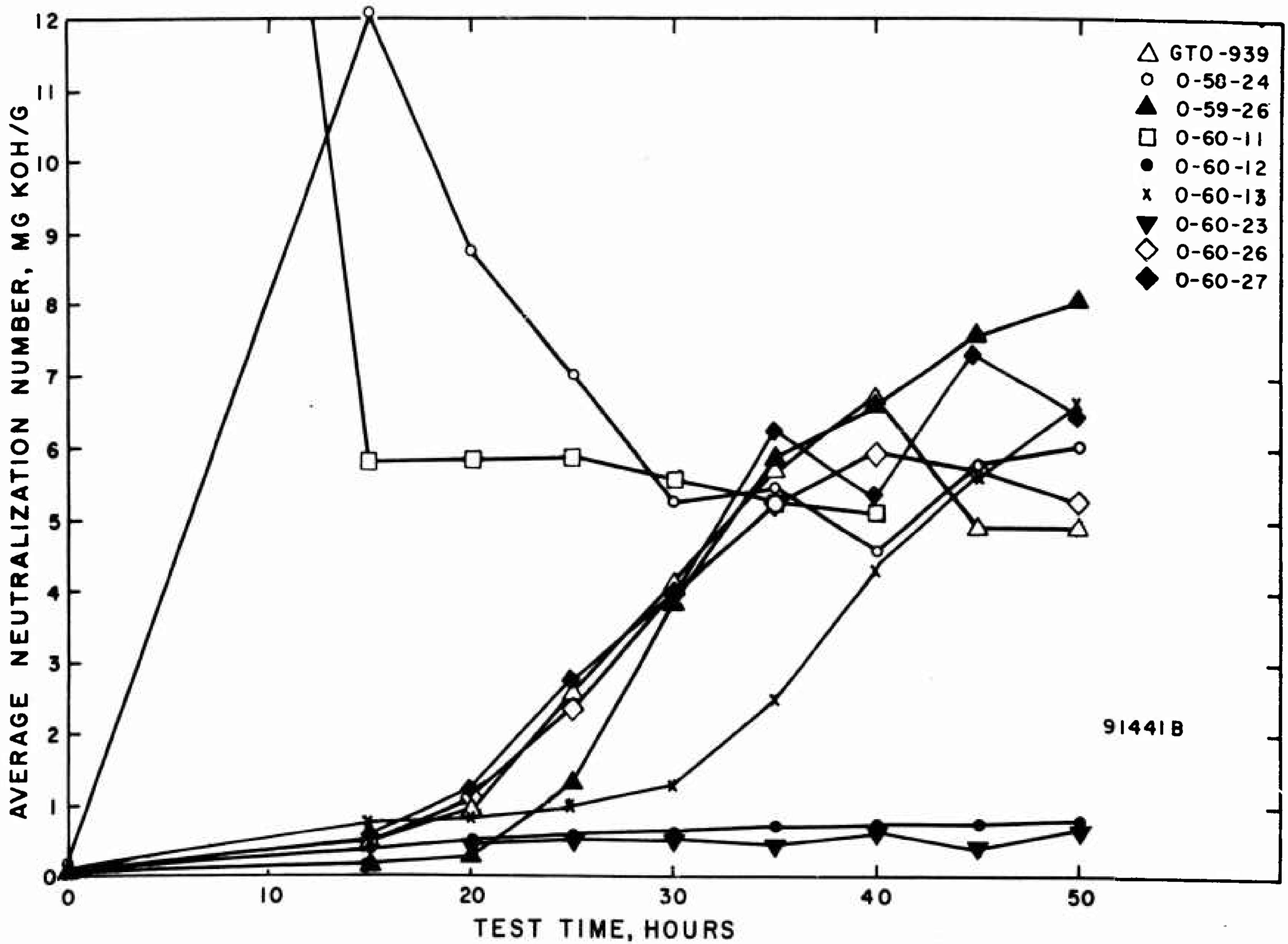


FIGURE 43. AVERAGE NEUTRALIZATION NUMBERS FOR NINE DIFFERENT LUBRICANTS VERSUS TEST TIME

determinations for each lubricant, from which the average results were calculated, are presented in Appendix IV (Tables 56 through 67).

It will be noted from Table 27 that 0-58-24 had an excessively large increase in viscosity at the start of the test which continued throughout the 50-hour test period, and consequently could not be completely included in Figure 42. It will be further noted from Table 27 and Figure 42 that three of the lubricants (0-60-11, 0-60-12, and 0-60-23) showed no significant increase in viscosity in 50 hours, while the five remaining lubricants (GTO-939, 0-59-26, 0-60-13, 0-60-26, and 0-60-27) showed noticeable increasing viscosity values after approximately 25 hours. From Figure 43, it will be readily noted that 0-60-12 and 0-60-23 showed no significant increase in neutralization number at the end of 50 hours. Referring again to Table 27 and Figure 43, it was found that 0-60-11 had a large initial neutralization number which decreased rapidly through the first 15 test hours and then remained practically constant for the remainder of the test.

In both Figures 42 and 43, it is interesting to note that the curves for GTO-939, 0-60-26 and 0-60-27 (different batches of the same material) are very similar even though the actual values are somewhat different. Of further interest is the fact that the test appears to give good repeatability between individual test cells tested during the same 50-hr period, as shown by the individual determinations of all fluids tested (Tables 56 through 67 in Appendix IV). In addition, when repeat tests were conducted on four different fluids (0-60-12, 0-60-13, 0-60-23, and 0-60-27) at different test periods, it appears that the repeatability of test results obtained during different 50-hr test periods was also good.

Since the program is still in progress and complete data have not been received from WADD for all of the oils included in the program, no comparison of Celanese oxidation test results with bearing rig or engine performance is attempted in this report.

Table 28 presents a summary of the weight changes of the metal specimens for all of the tests reported in Tables 56 through 67 in Appendix IV. It will be noted that all of the weight changes were reasonably repeatable and that, of the five metals included, only copper suffered a distinct weight loss with all the fluids tested.

A comparison of the Celanese oxidation test data obtained by SwRI has been made with the data obtained from the Celanese Chemical Company. Table 29 presents the average individual test results obtained by the two laboratories using two test fluids. The individual determinations obtained by each laboratory, from which these average values were obtained, are presented in Tables 60, 61, 63, 66, and 67 in Appendix IV. It will be noted that

TABLE 28. SUMMARY OF WEIGHT CHANGES OF METAL SPECIMENS IN CELANESE OXIDATION TEST

Oil Code	Test Starting Date	Weight Change, mg/sq cm				
		Aluminum	Titanium	Silver	Copper	Steel
GTO-939	10-31-60	-0.069	-0.038	-0.054	-2.930	-0.062
	10-31-60	-0.023	-0.054	-0.069	-2.589	0.000
	10-31-60	-0.054	-0.093	-0.093	-1.666	-0.015
0-58-24	11-7-60	+0.069	+0.178	+0.038	-15.302	+0.232
	11-7-60	+0.038	+0.069	-0.116	-16.395	+0.031
	11-7-60	+0.015	+0.007	+0.077	-18.666	+0.046
0-59-26	12-12-60	+0.038	+0.038	+0.062	-0.294	-0.100
	12-12-60	-0.031	-0.031	-0.100	-0.426	0.000
	12-12-60	+0.015	+0.007	-0.023	-0.403	-0.015
0-60-11	11-28-60	+0.038	+0.062	+0.069	-0.449	+0.038
0-60-12	10-31-60	0.000	-0.100	-0.093	-0.581	-0.054
(D-1074)	10-31-60	-0.100	-0.046	-0.054	-0.550	-0.085
	10-31-60	-0.069	-0.015	-0.085	-0.511	-0.038
0-60-12	12-5-60	-0.054	-0.031	-0.031	-0.480	-0.007
(D-1087)	12-5-60	+0.015	+0.023	-0.015	-0.403	0.000
	12-5-60	+0.007	+0.031	+0.023	-0.263	+0.007
0-60-13	11-7-60	+0.054	+0.069	+0.023	-0.658	+0.038
	11-7-60	+0.069	+0.085	+0.186	-0.689	+0.054
	11-7-60	+0.046	+0.100	+0.077	-0.837	+0.108
	12-27-60	+0.038	0.000	-0.007	-0.906	+0.062
	12-27-60	+0.031	+0.023	+0.038	-0.945	+0.085
	12-27-60	+0.069	+0.069	+0.062	-0.813	+0.100
0-60-23	10-3-60	-0.108	-0.062	-0.100	-0.457	-0.062
	10-3-60	-0.077	-0.023	-0.062	-0.480	-0.031
	10-3-60	-0.062	-0.007	-0.015	-0.434	-0.031
	10-3-60	-0.054	-0.023	-0.023	-0.364	-0.023
	10-3-60	-0.062	-0.023	-0.015	-0.441	-0.046
	10-17-60	-0.023	-0.054	0.000	-0.317	-0.045
	10-17-60	-0.054	-0.124	-0.046	-0.310	-0.045
	10-17-60	-0.031	-0.054	-0.035	-0.209	-0.035
	11-28-60	-0.023	-0.007	-0.015	-0.472	-0.062
0-60-26	12-12-60	-0.031	-0.007	-0.038	-0.953	0.000
	12-12-60	0.000	+0.031	-0.023	-0.806	+0.062
	12-12-60	-0.046	-0.031	-0.069	-0.852	-0.031
0-60-27	10-17-60	-0.023	-0.077	-0.031	-1.062	-0.093
	10-17-60	-0.077	-0.077	-0.031	-1.062	-0.124
	10-17-60	-0.038	-0.038	0.000	-0.883	-0.031
	12-5-60	+0.046	+0.069	+0.031	-1.062	+0.054
	12-27-60	-0.007	+0.054	-0.007	-1.116	+0.069
	12-27-60	-0.015	-0.062	-0.062	-1.170	-0.007
	12-27-60	0.000	+0.007	-0.046	-0.961	-0.015

TABLE 29. COMPARISON OF AVERAGE OXIDATION TEST RESULTS OBTAINED BY TWO LABORATORIES FOR 0-60-12 AND 0-60-23

Oil Code	Laboratory	Tests	Test Time, hours 0	15	20	25	30	35	40	45	50	Total Overhead Acidity mg KOH/g
0-60-12[a] (D-1074)	SwRI	Viscosity, cs at 100°F	16.14	17.71	18.05	18.07	18.19	18.58	18.91	18.96	19.25	4.97
		Neut. No., mg KOH/g	0.13	0.41	0.51	0.61	0.61	0.71	0.73	0.77	0.77	
		Make-up, g		7.8	11.0	14.0	10.5	6.2	11.2	10.2	8.7	
0-60-12[b] (D-1087)	SwRI	Viscosity, cs at 100°F	16.12	17.57	17.65	17.95	18.11	18.45	21.37	18.82	19.13	3.81
		Neut. No., mg KOH/g	0.03	0.41	0.38	0.39	0.45	0.47	0.47	0.48	0.53	
		Make-up, g		9.5	11.7	10.5	9.8	9.2	10.7	9.5	9.2	
0-60-12	Celanese	Viscosity, cs at 100°F	15.92	-	18.01	18.00	18.22	18.44	18.64	18.81	-	5.2
		Neut. No., mg KOH/g	<0.05	-	0.48	0.42	0.55	0.51	0.54	0.61	-	
		Make-up, g		-	12.0	10.8	11.0	10.0	9.8	8.3	-	
0-60-23	SwRI	Viscosity, cs at 100°F	16.02	17.30	17.45	17.63	17.86	17.96	18.11	18.23	18.49	4.03
		Neut. No., mg KOH/g	0.05	0.37	0.44	0.42	0.45	0.54	0.63	0.54	0.68	
		Make-up, g		11.4	11.0	10.1	10.3	8.9	8.5	10.1	11.5	
0-60-23	Celanese	Viscosity, cs at 100°F	16.11	-	17.19	18.26	18.64	20.42	25.50	31.13	-	26.8
		Neut. No., mg KOH/g	0.06	-	0.42	0.44	0.72	1.83	4.00	5.93	-	
		Make-up, g		-	10.5	9.0	10.5	10.5	16.0	14.0	-	

Celanese oxidation test procedure was used by both laboratories. Average test results obtained from individual determinations listed in the appendix.
(a) Oil received from manufacturer.
(b) Oil received from WADD.

the test results obtained for 0-60-12 are in good agreement. However, the test results obtained for 0-60-23 showed a significant difference between the two laboratories. The reasons for the differences noted with 0-60-23 have not been determined. Before any definite conclusion for this phase of the program can be made, additional data are needed from both laboratories.

E. Conclusions

No definite conclusions can be made with respect to the Celanese oxidation test apparatus and procedure since the data obtained during this contract period are not sufficient for a general evaluation. However, from the test results obtained to date, the Celanese oxidation test apparatus and procedure appear to have a promising prospect of yielding a reasonable degree of repeatability and reproducibility.

V. IMPACT SENSITIVITY

A. General Remarks

The objectives of this phase of the program were to investigate the different inherent variables of the ABMA* impact test in an effort to further improve the repeatability and reproducibility of the impact sensitivity tests, to develop a standardized test method for determining the impact sensitivity of lubricants and greases in contact with liquid oxygen, and to design and construct an impact tester, similar to the ABMA impact tester, which can satisfactorily be used with either liquid oxygen or nitrogen tetroxide.

During the previous contract period, an impact test facility was set up in a temporary location, and used in a program of instrumentation development and preliminary experimentation. During this contract period, the impact tester was relocated from the temporary location to a permanent impact test facility specifically constructed for this purpose at the expense of SwRI. The drop time of the plummet was retested after the tester was moved to the new location. The repeatability of the time measurements, in terms of maximum scatter from the average value was within one percent. The error of the measured drop time from the computed theoretical free fall time was between 2 and 2.5 percent for all drop distances tested.

An impact sensitivity Cooperative Test Program No. 2 and its preliminary test program, initiated by WADD, has been completed during this contract period. Impact sensitivity test data were obtained on the six test samples selected for these programs.

The improvement of the repeatability of the impact sensitivity test has been one of the main objectives of this program; in this concern, investigations were conducted on the various aspects to achieve this end. It has been found that sample thicknesses below 0.040 in. appreciably affect the sensitivity of the sample and that with a constant volume of different test samples, the thickness of the sample varies with the physical properties of the test samples and the types of specimen cups used. An investigation has been conducted on the effect of sample floating on the impact sensitivity of frozen fluid sample. On the basis of these investigations, repeatability tests were conducted using three different fluid samples and satisfactory results have been obtained. In an effort to find a standard reference sample fluid to be used in future cooperative programs, 16 sample fluids submitted by WADD have been tested and two of these samples, CG-18 and CG-35 were selected as tentative reference samples.

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*Army Ballistic Missile Agency, now George Marshall Space Flight Center.

Apparatus for grease sample preparation have been fabricated according to WADD design and other necessary equipment has been procured. In addition, a complete set of drawings for a proposed standard impact tester has been submitted to WADD for approval along with a proposed standard test procedure.

B. Development of ABMA Impact Tester

The new impact test facility was completed. The new facility consists of three separate rooms; the test cell in which the impact tester is located, an air-conditioned laboratory room which contains the instrumentation for the impact tester and the necessary support equipment for preparing samples and cleaning test parts, and a room for storing the oxidizers. The complete test facility will be briefly described.

1. ABMA Impact Tester

The ABMA impact tester was fabricated at WADD according to ABMA design.[11, 14] A schematic diagram of this tester is presented in Figure 44. This tester consists of a plummet assembly, weighing 20 ± 0.05 lb, which is guided in its vertical travel by three guide rails. Friction between the plummet assembly and the guide rails is minimized by the use of six small rollers, three each attached to both upper and lower spider plates of the plummet assembly. The plummet assembly may be held at any desired vertical height, between 0 and 50 in., by means of an electromagnet, which is clamped to a fourth rail and whose position on the fourth rail is adjustable. The plummet may be released by de-energizing the magnet, whereupon it is allowed to drop upon a striker pin which had previously been placed in position in a specimen cup containing the test sample and the oxidizer. Observations are made as to whether a reaction occurs as a result of the impact, the nature of the reaction, and the measured drop time of the plummet.

Relocation of Impact Tester. The ABMA impact tester was relocated from the original temporary location to the permanent impact test facility recently completed. No major change was made to the impact tester or its instrumentation; however, the original impact tester base, made of angle iron in the form of a truncated pyramid, was filled with concrete to form a more rigid, permanent base for the impact tester. A photograph of the relocated impact tester is shown in Figure 45.

The walls and ceiling of the permanent test cell, in addition to the permanent impact tester base, were covered with aluminum sheets to minimize dust collection and facilitate cleaning. A steel panelled, sliding door separates the test cell from the laboratory room.

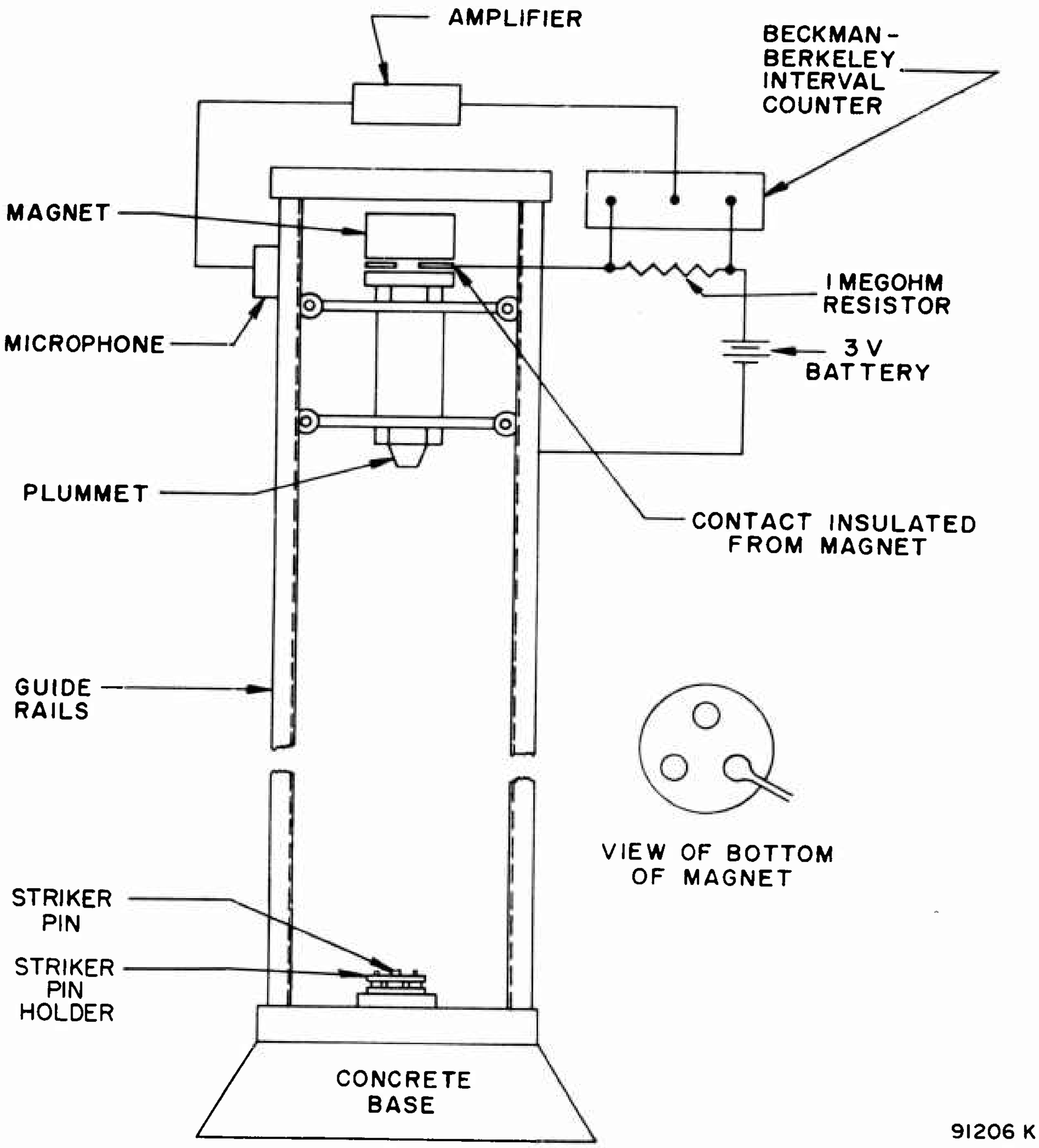


FIGURE 44. SCHEMATIC DIAGRAM OF ABMA IMPACT TESTER SHOWING INSTRUMENTATION FOR MEASUREMENT OF DROP TIME

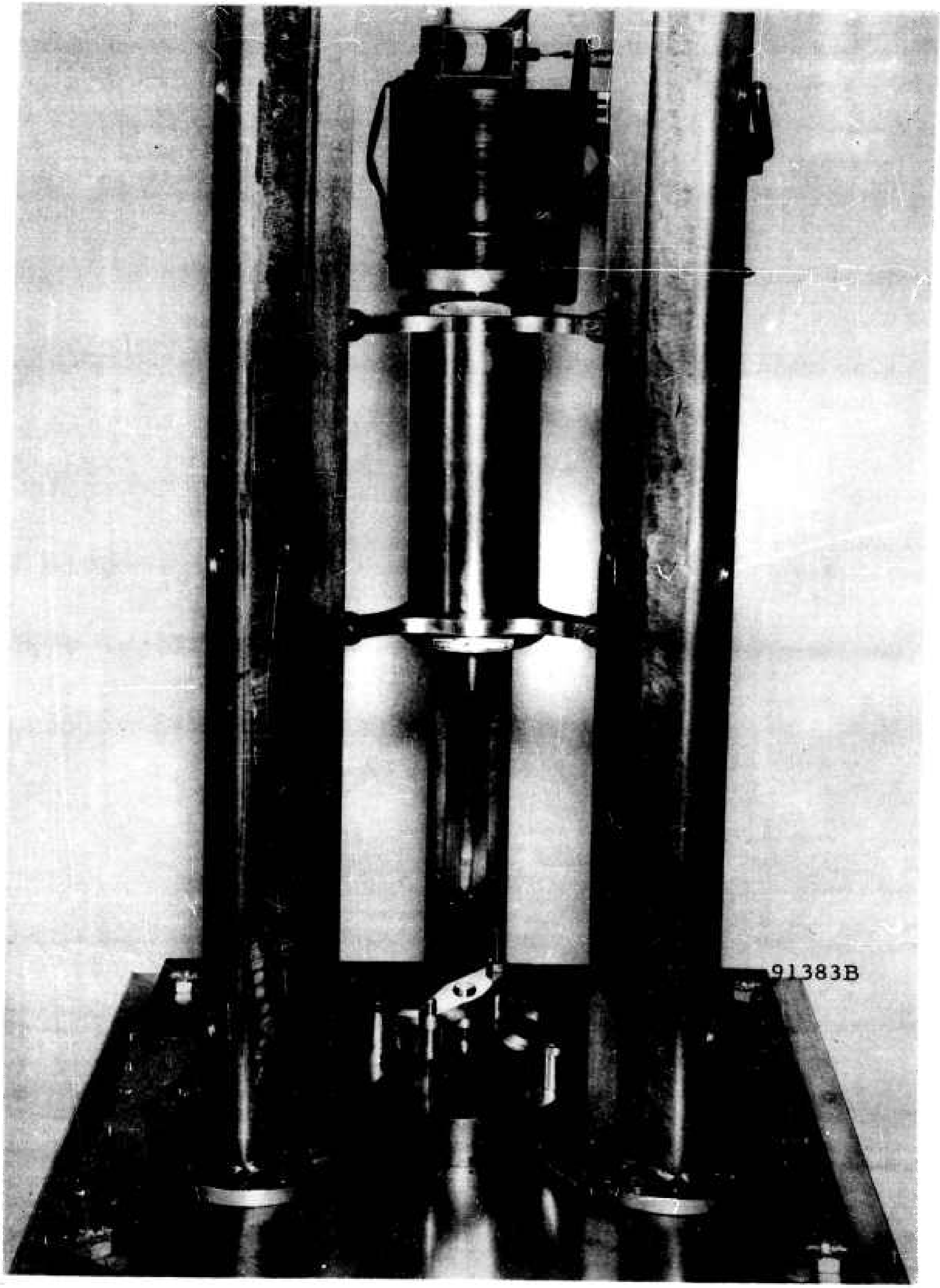


FIGURE 45. PHOTOGRAPH OF THE ABMA IMPACT TESTER

Recalibration of Plummet Drop Time. After the relocation of the impact tester was completed, the drop time of the plummet was retested. Table 30 shows the results of time measurements for drop distances of 10, 20, 30, 40, and 50 inches. It will be noted that the repeatability of the time measurements, in terms of maximum scatter from the average value, was within one percent. The error, or the departure of the average observed drop time from the computed theoretical free fall time was between 2 and 2.5 percent for all drop distances tested.

Instrumentation. No changes have been made to the impact test instrumentation, except for relocation to the new facility, from that previously reported.(0.85)

2. Minor Modifications of the ABMA Impact Tester

In order to facilitate cleaning of the anvil region assembly and alignment of this assembly with the base plate, the specimen cup holder hold-down springs and retaining bolts were replaced with two 2-1/2 in. stainless steel bolts which bear on the hold-down toes through two stainless steel flat washers. This change also prevents the specimen cup holder from jumping out from the recess on the anvil plate when a violent reaction occurs. It will be noted that the new anvil region assembly is included in Figure 45.

The magnetic plate on the top of the plummet was cadmium plated to prevent rusting. Since the cadmium plating was found to have very little, if any, effect on the magnetic properties of the steel plate, it is recommended that the entire electromagnet assembly be cadmium plated.

A complete set of drawings for the proposed standard ABMA type impact tester was prepared and submitted to WADD for approval. The major deviations from the original ABMA design are the electromagnet assembly, the strut assemblies, and the anvil region assembly. The electromagnet assembly recommended by SwRI requires a lower voltage than the original ABMA design. The strut assemblies proposed differ from the ABMA design only in the shape of the area cross section of the strut (all critical dimensions remain the same). The major proposed change from the ABMA design is the anvil region assembly. The proposed anvil region assembly design has a solid steel anvil plate and specimen cup holder that locates the specimen cup rather than a liquid gas reservoir type holder.

3. Test Equipment

Striker Pins. In order to replenish the SwRI supply of striker pins and supply the cooperative laboratories with sufficient pins to conduct the Cooperative Test Program No. 2, 1000 striker pins, made to USAF-AMC

TABLE 30. RESULTS OF DROP TESTS AFTER RELOCATION OF IMPACT TESTER

Drop Test No.	Drop Time, sec 10 in.	20 in.	30 in.	40 in.	50 in.
1	0.2332	0.3297	0.4028	0.4623	0.5193
2	0.2329	0.3302	0.4034	0.4650	0.5196
3	0.2327	0.3301	0.4048	0.4670	0.5204
4	0.2343	0.3300	0.4033	0.4643	0.5200
5	0.2332	0.3300	0.4042	0.4664	0.5221
6	0.2326	0.3301	0.4047	0.4641	0.5241
7	0.2335	0.3300	0.4050	0.4672	0.5194
8	0.2325	0.3298	0.4023	0.4643	0.5244
9	0.2332	0.3298	0.4032	0.4648	0.5195
10	0.2347	0.3292	0.4028	0.4654	0.5254
Avg. Drop Time, sec	0.2333	0.3299	0.4036	0.4651	0.5214
Max. Scatter, %	+0.60 -0.34	+0.09 -0.21	+0.35 -0.32	+0.45 -0.60	+0.76 -0.40
Computed Time of Free Fall, sec	0.2278	0.3221	0.3945	0.4556	0.5093
Error from Time of Free Fall, %	2.4	2.4	2.3	2.0	2.3

drawing X57A9570, were ordered. Upon receipt of these striker pins, each pin was visually inspected, and dimensional inspections were made at random and found to be within the specified tolerances. However, when these pins were tested for deformation (by running blank tests at a plummet drop height of 48 in.), it was found that the diameter of the pins tested increased in the order of 0.010 in. after the first drop. This increase in diameter exceeds the normal maximum tolerance limit of the mating hole in the striker pin holder, making it necessary to force the pin out from the holder after each test. An increase in striker pin diameter of this magnitude had never occurred previously, and it definitely is not desired.

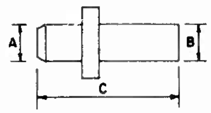
A chemical analysis of the striker pin material (MIL-S-7720, Composition 316) was obtained from the steel supplier and also an independent laboratory. The results from both sources checked satisfactorily and proved to be within the composition limits set by the military specification. Hardness determinations were then made on both the new striker pins that had failed by deforming and the old striker pins that had performed satisfactorily. Both sets of hardness data obtained were found to be within the hardness range for this annealed material. Upon checking the material grain size in a striker pin that had performed satisfactorily and one that had deformed during an impact test, it was found that the striker pin that had performed satisfactorily had a very uniform, fine grain size, while the one that had deformed did not have a uniform grain size and had evidence of incipient grain growth, indicating improper annealing by the manufacturer.

In an effort to find a more satisfactory striker pin material, six striker pins were fabricated and heat treated from each of three different stainless steel compositions (A-286, 17-4PH and 17-7PH). The new striker pins were heat treated to an average hardness of C-33 for A-286, C-43 for 17-4PH, and C-44 for 17-7PH.

In order to test the new striker pins for deformation after an impact drop, each pin was cooled in liquid oxygen and then subjected to three standard blank tests. The diameters and length of each pin were measured before the blank tests and after each succeeding blank test. Table 31 presents the measurements obtained as well as the final deviation, if any, from the original dimension. It will be noted that there was practically no dimensional change for the striker pins made from the 17-4PH and 17-7PH materials, while a measurable change in dimensions was noted for all of the striker pins made of the A-286 material.

For further testing of the 17-4PH and the 17-7PH striker pins, they were used in regular impact tests and their dimensions were measured again after 16 drops. The results of these measurements are presented in Table 32. It will be noted that both sets of pins show very little, or no change from their respective original dimensions.

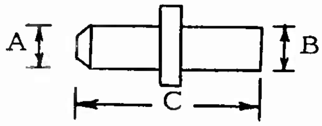
TABLE 31. MEASUREMENTS OF STRIKER PINS AFTER FIRST THREE DROP TESTS



Pin Material and No.	Hardness	Striker Pin Measurements, in.														
		A_o	A_1	A_2	A_3	A_3-A_o	B_o	B_1	B_2	B_3	B_3-B_o	C_o	C_1	C_2	C_3	C_o-C_3
17-4-1	C-43	.498	.498	.498	.498	0	.498	.498	.498	.498	0	2.003	2.003	2.002	2.002	.001
17-4-2	C-43	.498	.498	.498	.498	0	.498	.498	.498	.498	0	1.999	1.999	1.999	1.999	0
17-4-3	C-41	.498	.498	.498	.498	0	.499	.499	.499	.499	0	2.001	2.001	2.001	2.001	0
17-4-4	C-44	.498	.498	.498	.498	0	.498	.498	.498	.498	0	2.001	2.001	2.001	2.001	0
17-4-5	C-43	.498	.498	.498	.498	0	.498	.498	.498	.498	0	1.998	1.998	1.998	1.998	0
17-4-6	C-43	.498	.498	.498	.498	0	.498	.498	.498	.498	0	2.002	2.002	2.002	2.002	0
A-286-1	C-33	.499	.503	.505	.507	.008	.499	.502	.503	.504	.005	2.002	1.986	1.976	1.968	.034
A-286-2	C-34	.499	.503	.505	.507	.008	.499	.502	.504	.505	.006	2.004	1.988	1.978	1.969	.035
A-286-3	C-33	.498	.502	.505	.507	.009	.498	.501	.503	.504	.006	2.003	1.987	1.976	1.967	.036
A-286-4	C-34	.499	.503	.505	.507	.008	.499	.502	.503	.505	.006	2.003	1.987	1.975	1.967	.036
A-286-5	C-32	.497	.501	.503	.505	.008	.498	.502	.504	.505	.007	2.001	1.984	1.973	1.968	.033
A-286-6	C-34	.498	.502	.505	.507	.009	.499	.502	.504	.505	.006	2.000	1.984	1.974	1.966	.034
17-7-1	C-44	.498	.498	.498	.498	0	.498	.498	.498	.498	0	2.012	2.012	2.012	2.012	0
17-7-2	C-45	.498	.498	.498	.498	0	.498	.498	.498	.498	0	2.003	2.002	2.002	2.002	.001
17-7-3	C-45	.498	.498	.498	.498	0	.498	.498	.498	.498	0	2.008	2.008	2.007	2.007	.001
17-7-4	C-44	.498	.498	.498	.498	0	.498	.498	.498	.498	0	2.007	2.007	2.007	2.007	0
17-7-5	C-44	.498	.498	.498	.498	0	.498	.498	.498	.498	0	2.013	2.013	2.013	2.013	0
17-7-6	C-43	.498	.498	.498	.498	0	.498	.498	.498	.498	0	2.007	2.007	2.007	2.007	0

The subscript o indicates the original dimension; subscripts 1, 2 and 3 indicate dimensions after the 1st, 2nd and 3rd drops respectively.

TABLE 32. MEASUREMENTS OF STRIKER PINS AFTER 16 DROP TESTS



Pin No.	Striker Pin Measurements, in.					
	A_o	A_{16}	B_o	B_{16}	C_o	C_{16}
17-4-1	.498	.498	.498	.498	2.003	2.002
17-4-2	.498	.498	.498	.498	1.999	1.999
17-4-3	.498	.498	.499	.499	2.001	2.001
17-4-4	.498	.498	.498	.498	2.001	2.001
17-4-5	.498	.498	.498	.498	1.998	1.998
17-4-6	.498	.498	.498	.498	2.002	2.002
17-7-1	.498	.498	.498	.498	2.012	2.011
17-7-2	.498	.498	.498	.498	2.003	2.002
17-7-3	.498	.498	.498	.498	2.008	2.007
17-7-4	.498	.498	.498	.498	2.007	2.007
17-7-5	.498	.498	.498	.498	2.013	2.012
17-7-6	.498	.498	.498	.498	2.007	2.007

The subscript o indicates the original dimension; subscript 16 indicates the dimension after 16 drop tests.

Both sets of striker pins have been used regularly since the aforementioned tests and no deformation has been observed. However, one of the pins made of material 17-7PH exhibited a pitting mark on the striking surface after a reaction and had to be remachined. After ascertaining that the durability, machinability and resistance to corrosion of the material was satisfactory, material 17-4PH was finally selected as the material to be used for the fabrication of future standard striker pins.

In an effort to improve the repeatability of the ABMA impact test, WADD studied two types of striker pins (the standard and the modified types). The modified striker pin consisted of a standard striker pin remachined to seat a 1/2-in. diameter, 52100 steel ball which is held in position at the end of the striker pin by a stainless steel spring sleeve. Since the modified striker pin had the same point contact area regardless of its alignment in the specimen cup due to the ball shape of the striking area of the striker pin, it was hoped that the problem of possible misalignment of the standard striker pin could be eliminated.

When both sets of these striker pins were used in impact tests, various reactions were observed in the case of standard striker pins with both normal and floated samples, but regardless of the condition of the frozen samples, no reaction was observed at the highest drop height when the modified striker pins were used. Assuming that adiabatic compression still occurred when a striker pin was misaligned, it would be conceivable that the misalignment problem might not be as significant as originally anticipated since unit loading did not appear to be as significant as adiabatic compression. It was therefore concluded that the present design of striker pins will be accepted as part of the standard equipment for the ABMA impact tester.

Specimen Cups. The aluminum specimen cups used to date with the ABMA impact tester at SwRI have been obtained from three sources; the first lot was obtained from ABMA, the second lot was obtained from WADD, and the third lot was obtained by SwRI from a local manufacturer. Although all specimen cups were supposedly manufactured to conform with the dimensions specified by USAF-AMC drawing X57A9564, inspection of random samples from the three different sources revealed that one important dimension (the inside radius of the bottom corner of the specimen cup) was not the same for all cups as shown in Table 33. Figure 46 presents a photograph of a typical sectioned specimen cup from each different source. It will be noted from Table 33 that the inside and outside diameter measurements also vary to a small degree. However, the variations found in these two dimensions are within the manufacturing tolerance limits for all the cups inspected.

The test procedure used in Cooperative Test Program No. 2 as well as in Pre-Cooperative Test Program No. 2 specified a fixed volume of

TABLE 33. COMPARISON OF MEASUREMENTS OF SPECIMEN CUPS FROM SwRI, WADD, AND ABMA

Specimen Cup No.	Bottom Corner Radius, in. Inside	Bottom Corner Radius, in. Outside	Bottom Thickness, in.	Inside Diameter, in.	Outside Diameter, in.
SwRI Cups					
1	0.078	0.140	0.063	0.870	0.999
2	0.062	0.140	0.063	0.874	0.999
3	0.062	0.156	0.063	0.869	0.999
4	0.062	0.140	0.062	0.871	0.998
5	0.062	0.140	0.063	0.868	0.999
WADD Cups					
1	0.125	0.172	0.063	0.870	0.997
2	0.109	0.172	0.063	0.870	0.997
3	0.125	0.172	0.062	0.871	0.998
4	0.125	0.172	0.062	0.871	0.997
5	0.125	0.172	0.063	0.870	0.997
ABMA Cups					
1	(a)	(a)	0.064	0.874	0.995
2	(a)	(a)	0.064	0.873	0.994
3	(a)	(a)	0.064	0.873	0.993
4	(a)	(a)	0.063	0.875	0.994
5	(a)	(a)	0.063	0.873	0.994
Nominal Specified Dimension[b]	0.126	0.188	0.062	0.871	0.995

(a) Not a true radius.

(b) Taken from USAF-AMC drawing X-57A9564.

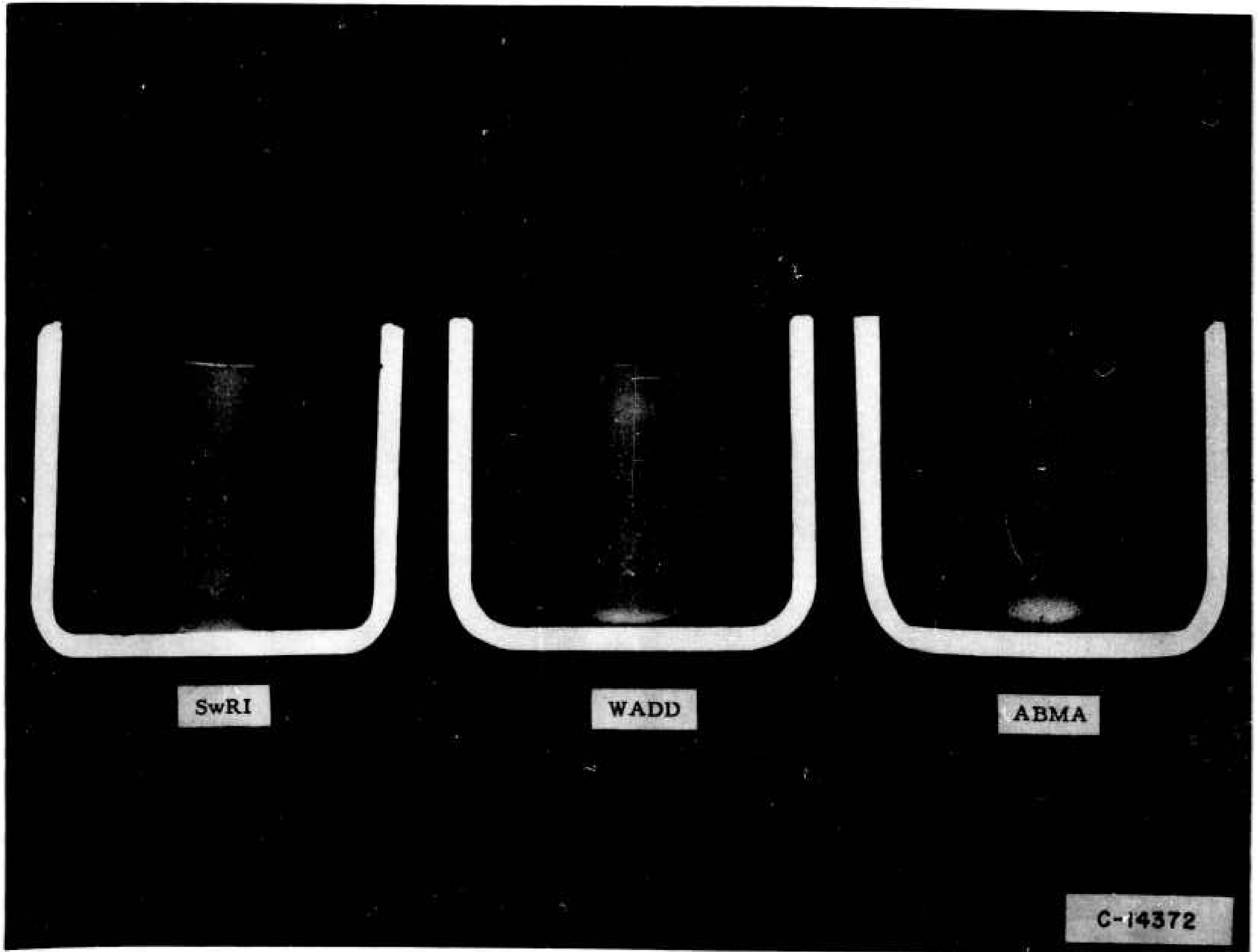


FIGURE 46. PHOTOGRAPH OF SECTIONED SPECIMEN CUPS FROM THREE DIFFERENT SOURCES

test sample to be used to obtain a desired test sample thickness in the specimen cup (normally 0.050 in.). This being the case, it was apparent that the difference noted in the inside radii of the specimen cups from the different sources would produce varying test sample thicknesses, which in turn might affect the results of the test. In an effort to investigate this possible variable, six cups from each source were cleaned and a fixed volume of test sample (0.47 ml) was added to each cup. The test sample thickness was then measured in the center of each cup with a depth micrometer. This procedure was repeated using 11 different fluids. Table 34 presents a summary of the average sample thicknesses of the 11 test samples using the different specimen cups; these average values were obtained from six individual measurements. It will be noted in Table 34 that the average sample thickness varied as much as 0.012 in. when different samples were measured using the same type of specimen cup; and an even larger difference, as much as 0.019 in., was noted in sample thickness when the same test samples were measured in specimen cups from the three different sources.

The reason for the differences noted in the sample thicknesses when the 11 different samples were measured in the same cups was no doubt due to the effect of certain physical properties of the individual fluids. An investigation of these effects showed that each test sample surface tends to rise slightly onto the sides of the specimen cup because of the surface tension and the resulting adhesive force of the fluid on the side of the specimen cup. Therefore, the sample thickness, measured in the center of the cup, is dependent upon the magnitude of this adhesive force and will be different from that of the assumed perfectly level surface. An additional factor which may, in conjunction with surface tension, affect the thickness of the test sample is the specific gravity. Therefore, the surface tension and the specific gravity of each of the test samples were measured. These measurements are included in Table 34. It will be noted that no general relationship is evident when the sample thicknesses are compared to either their respective surface tension or specific gravity alone. However, by plotting the test sample thickness versus the ratio of surface tension to specific gravity, as shown in Figure 47, it appears that a general relationship does exist although no accurate prediction of test sample thickness could be made by means of this relationship.

ABMA has reported that reducing the test sample thickness from 0.050 to 0.004 inches, all other factors being equal, increases the sensitivity of certain test samples as much as 16 times.[11, 14] In view of this information, the data reported herein, and the present lack of an accurate method of predicting test sample thickness, it was decided that all future standard impact sensitivity tests should be conducted using a test sample thickness of 0.050 in., rather than a specified volume of test sample.

TABLE 34. SUMMARY OF AVERAGE SAMPLE THICKNESS MEASUREMENTS USING DIFFERENT TEST SAMPLES AND SPECIMEN CUPS FROM SwRI, WADD, AND ABMA

Test Sample	Avg. Sample Thickness, in. Specimen Cup Source			Specific Gravity	Surface Tension, dyne/cm	Surface Tension ÷ Specific Gravity
	SwRI	WADD	ABMA			
CG-5	0.038	0.047	0.055	1.0357	21.4	20.7
CG-9	0.035	0.046	0.053	1.0023	25.4	25.3
CG-18	0.032	0.041	0.049	0.9105	30.9	33.9
CG-26	0.044	0.053	0.058	1.9546	30.5	15.6
CG-34	0.042	0.053	0.058	1.0366	20.8	20.1
CG-35	0.039	0.049	0.055	1.0213	22.5	22.0
CG-61	0.037	0.048	0.055	1.1952	45.4	38.0
CG-62	0.037	0.047	0.055	1.0091	23.2	23.0
II-F	0.043	0.050	0.056	1.2261	28.7	23.4
500	0.034	0.043	0.053	1.0656	32.0	30.0
1248	0.033	0.042	0.051	1.4473	44.1	30.5

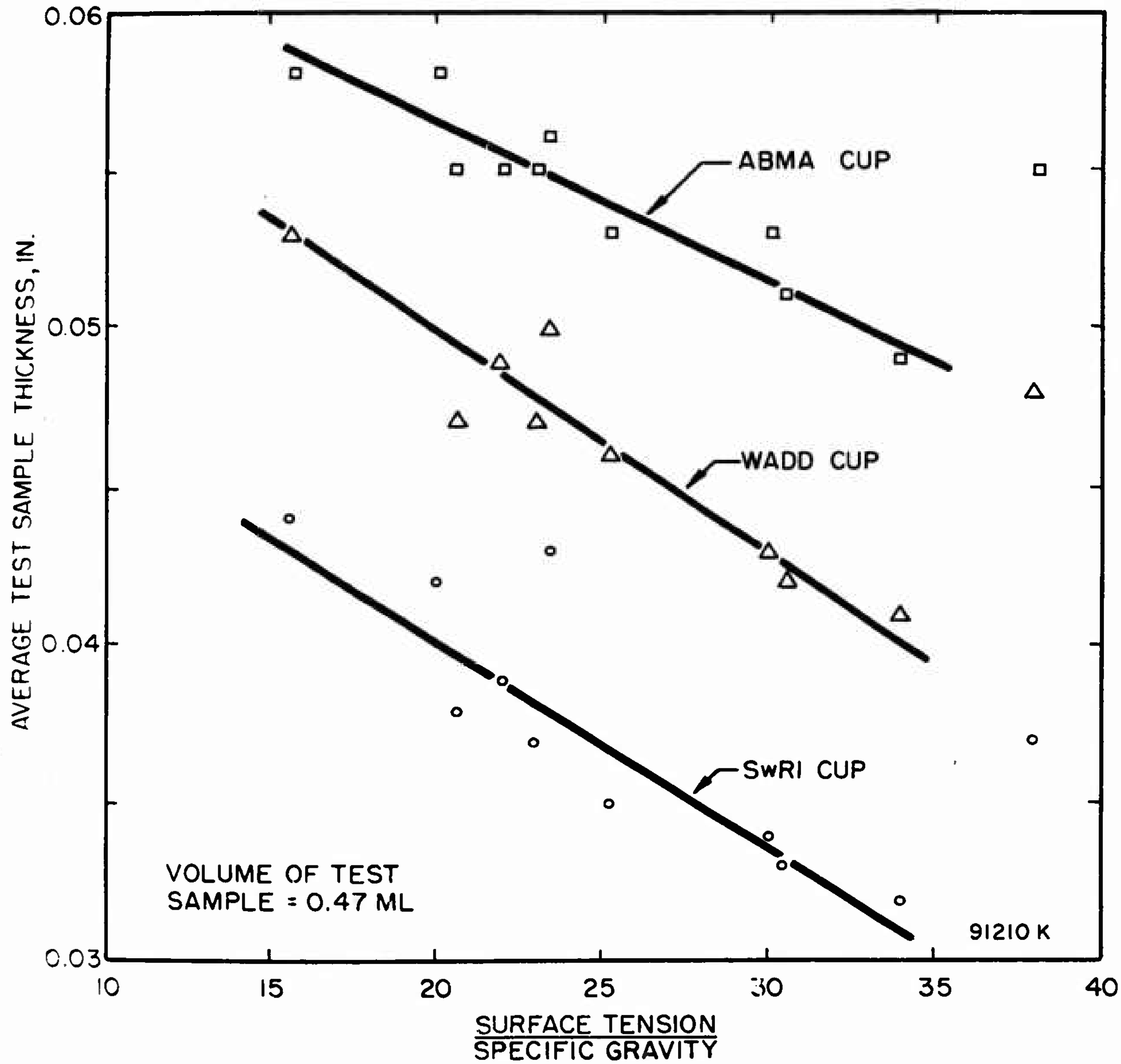


FIGURE 47. EFFECT OF SURFACE TENSION DIVIDED BY SPECIFIC GRAVITY ON TEST SAMPLE THICKNESS

Grease Sample Preparation Apparatus. A grease sample leveling slab and a sample cutter of WADD design have been fabricated for the preparationof grease samples. Figures 48 and 49 present the details of these apparatus. The remaining necessary equipment for the preparation of grease samples, such as the spatula and stainless steel wire, have been procured.

C. Impact Test Procedure Adopted by SwRI

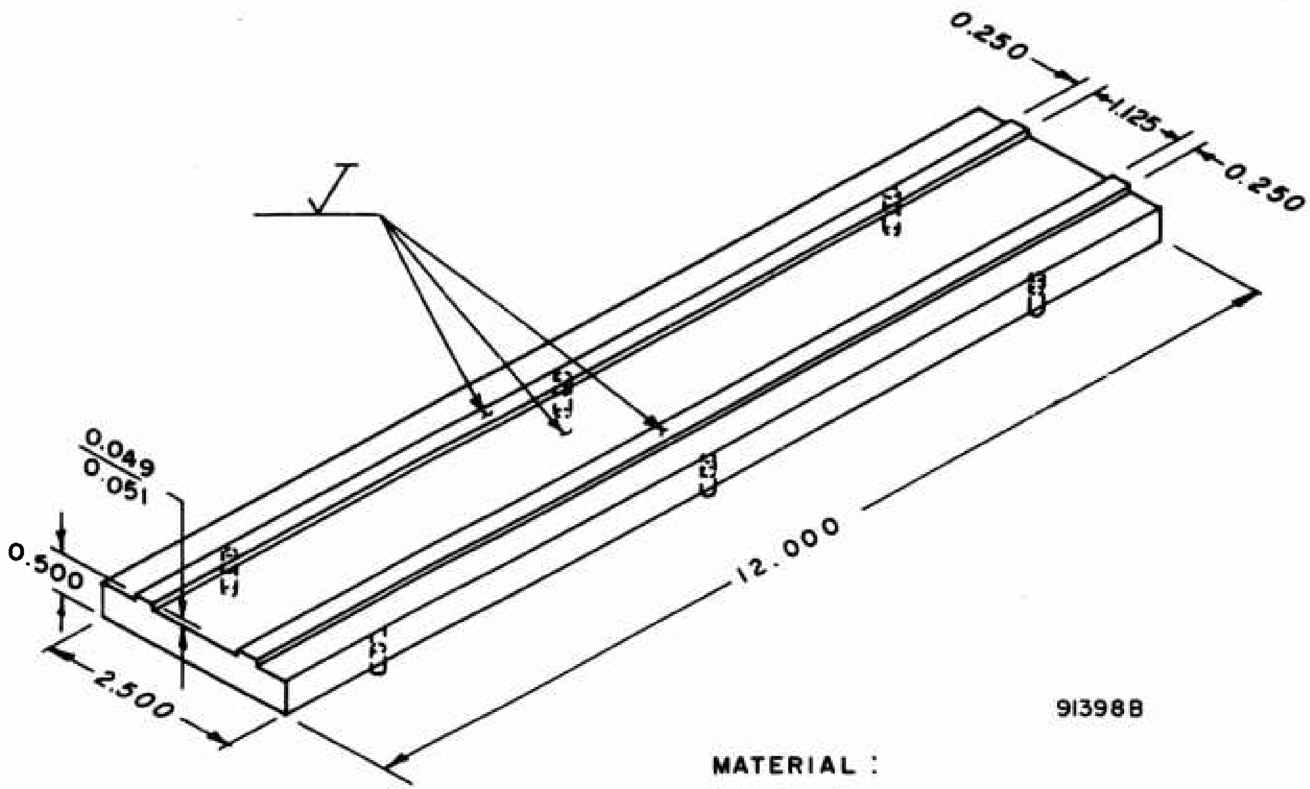
In an effort to improve the repeatability of the impact sensitivity test using the ABMA type impact tester, a tentative test procedure, including a detailed cleaning procedure, was submitted to WADD. After considerable study by WADD and SwRI, some revisions were made and the resulting test procedure has since been adopted by SwRI and WADD as the standard procedure for determining the impact sensitivity of oils and greases as well as other materials. The main points in this procedure will be discussed in the following paragraphs; for the details of this procedure, reference shall be made to "Tentative Liquid Oxygen Compatibility Impact Sensitivity Test Method" distributed by WADD.

1. Equipment Preparation

The impact tester, its accessories, and the test cell shall be maintained in a clean condition. The guide tracks, plummet, anvil plate, striker pin guide, specimen cup holder, and base plate shall be thoroughly cleaned between tests using steel wool and a final rinse with extraction grade trichloroethylene. The test area of the tester, which consists of the anvil plate, specimen cup holder, striker pin guide, and plummet nose, must be cleaned with extraction grade trichloroethylene at least after every 10 sample specimen cups have been impacted and more often if necessary. The levelness and perpendicularity of the tester shall be checked and maintained during testing. Tightening down the guide rails is frequently necessary to insure less drag of the plummet when dropping. Timing instrumentation will aid the operator in determining when to adjust the rig for more efficient operation.

The striker pins shall be cleaned by vapor degreasing with trichloroethylene, then soaked in an alkaline cleaner (15 grams Na_3PO_4 and 15 grams NaOH in one liter of distilled water) for 15 minutes followed by a thorough rinsing with distilled water, and then allowed to dry in air. Before placing each pin in the storage container after cleaning, an inspection of the striker pin contact area is necessary to insure that the contact area of the striker pin is free of scratches and pits and that the pin has not been flattened or bent excessively during tests. Those not passing inspection will be remachined or discarded.

1. SIX LEGS REQUIRED, $\frac{1}{8}$ DIA. X $\frac{1}{4}$ LONG
2. REMOVE BURRS & BREAK SHARP EDGES 0.010-R
3. SURFACES MARKED "√" TO HAVE 63√ FINISH AND MUST BE PARALLEL TO EACH OTHER WITHIN 0.001



91398B

MATERIAL :
ALUMINUM ALLOY QQ-A-318 (5052)
TEMPER H-32

FIGURE 48. WADD GREASE SAMPLE LEVELING SLAB

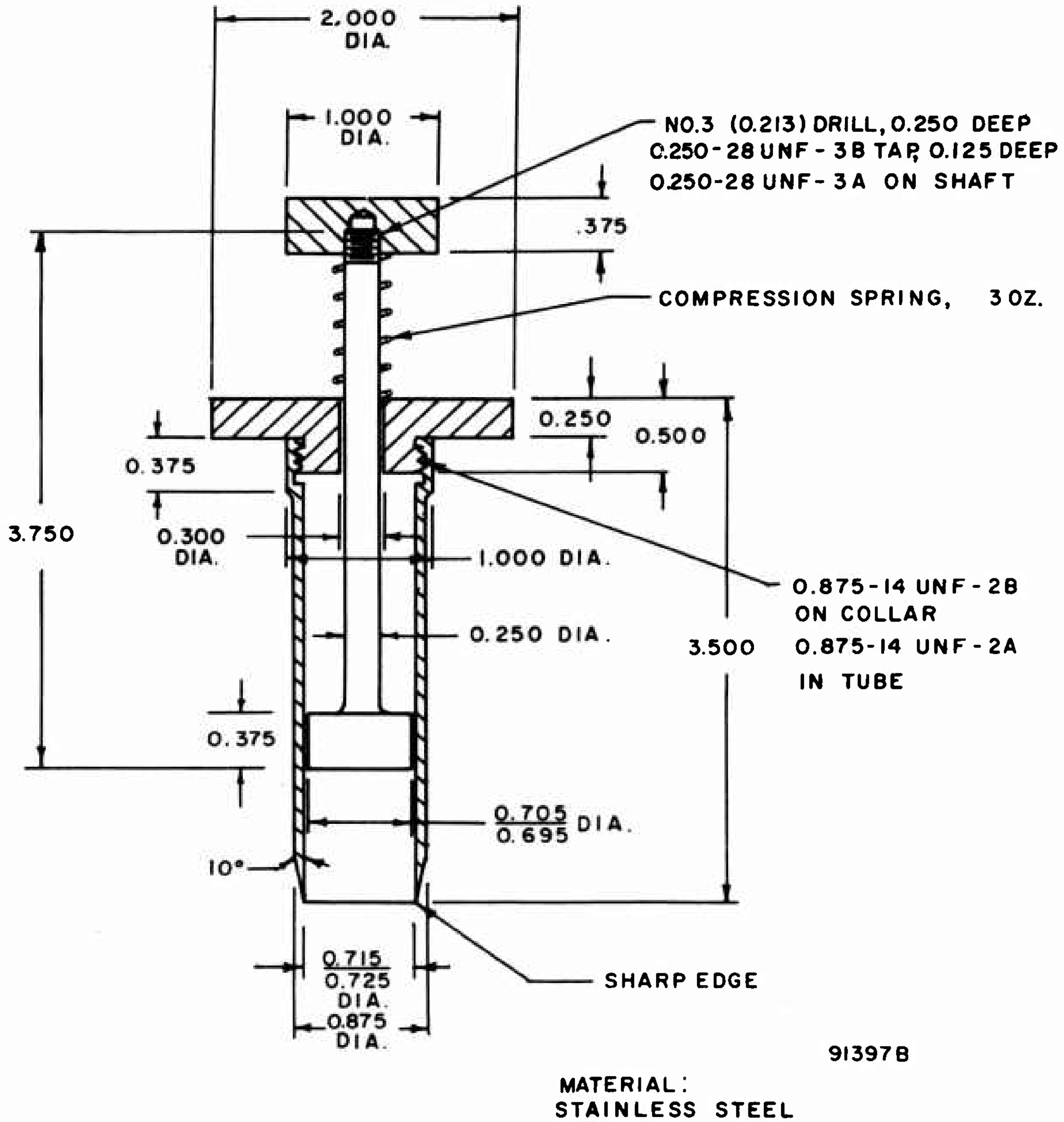


FIGURE 49. WADD GREASE SAMPLE CUTTER

The specimen cups shall be cleaned by vapor degreasing with trichloroethylene, detergent wash ("Tide" or its equivalent), distilled water rinse, isopropanol alcohol rinse, extraction grade trichloroethylene rinse, and then allowed to dry in air. Individual inspection of the interior base of the specimen cup is necessary to insure that it is free of scratches and pits before placing each cup in the storage container after cleaning. Those not passing inspection will be recleaned or discarded.

The forceps, specimen cup tray, grease sample leveling slab, spatula and any metal sample handling equipment shall be cleaned in the same manner as the test specimen cups. The sample handling glassware, such as the syringe or the microburette, shall be cleaned by soaking in a sulfuric acid-dichromate cleaning solution (about one hour) and rinsed with distilled water. The Dewar flasks shall be rinsed with extraction grade trichloroethylene and allowed to air dry.

2. Sample Preparation

For the preparation of an oil sample, the sample shall be shaken well or stirred if bubble formation is a problem in its original container before using. A sufficient amount of test sample shall be used to form a layer 0.050 ± 0.003 in. thick at the bottom of the specimen cups. After the volume of each test sample required to obtain this specified sample thickness is determined by measurement, a microburette or 1/2-ml syringe can then be used to measure out the required volume of test sample into at least 20 specimen cups (normally 24 cups with test sample are prepared in case a few of the frozen samples are not satisfactory for test). The specimen cups with sample shall then be precooled to the boiling point of liquid oxygen. The cooling method is an important factor and should be followed carefully.

A stainless steel tray (similar to a hospital pan) shall be placed on a level table to insure a uniform and level sample thickness. Specimen cups containing the sample are then placed in the tray. Liquid oxygen is then slowly poured into the tray to a depth of approximately 1/4-in. After the samples have been frozen, liquid oxygen shall then be poured into the pan until the liquid oxygen depth will permit the cups to float in the liquid oxygen. The specimen cups are filled with liquid oxygen by letting the liquid oxygen overflow the sides of the cups. The cups should be checked to assure that the sample has not separated from the bottom of the cups.

The test area should be precooled with liquid oxygen before setting the test specimen cup in the specimen cup holder. Immediately after precooling the test area, a specimen cup with test sample (or a blank cup)

filled with liquid oxygen is placed in the specimen cup holder. During this operation, a check should again be made to insure that no test sample has broken up and floated, leaving a void in the test sample surface. A clean striker pin, precooled by immersion in liquid oxygen shall then be placed in position, in contact with the test sample surface; and the specimen cup is topped with liquid oxygen just prior to the impact test drop. The sample is now ready for testing.

If the sample to be tested is a grease sample, it shall be packed into the channel of the sample leveling slab at room temperature with a spatula and leveled with a 10 B. S. gage stainless steel wire. The leveling slab is then placed on a solid carbon dioxide block to precool the leveled sample, after which it is cooled until solid by placing the slab in a level tray containing less than 3/4 inch of liquid oxygen. Before the sample is completely frozen and becomes brittle, the sample cutter is used to cut out the disc-shaped samples, the thickness of which are fixed at 0.050 in. by the 0.050-in. deep channel in the slab. The disc-shaped grease samples are transferred to the clean and precooled test specimen cups by means of the sample cutter. The remaining testing procedure will be the same as that used with oil samples.

It has been found that for some grease samples, it would be easier to separate the frozen grease samples from the sample preparation slab if a strip of 0.002-in. aluminum foil has been placed in the 0.050-in. deep channel and the grease sample is packed over this strip of foil. There is an alternate method for preparing grease samples by means of a hypodermic syringe and a centrifuge. However, this method has not been used to date at SwRI, and therefore, will not be discussed.

3. Impact Tests

Critical Test Parameters. Six critical test parameters shall be maintained within the limits as follows:

(1) Plummet weight shall be 20 ± 0.05 pounds.

(2) Drop time. If for a given test drop at a specified height the measured drop time deviates by more than ± 0.010 second from the average measured time for twenty test drops at the same height, then this test drop will not be counted as part of the twenty test drops. One additional test drop will be made to compensate for each discounted test drop.

(3) Drop distance. The maximum distance deviation from the drop height specified for a test drop is ± 0.2 inch.

(4) Striker pin diameter near the striking area shall be 0.500 ± 0.005 inch.

(5) Sample thickness shall be 0.050 ± 0.003 inch.

(6) Kinetic energy loss. The kinetic energy loss due to friction shall be indirectly limited to a maximum of approximately 6 percent of the potential energy for any given drop height by limiting the average measured drop time for 20 acceptable test drops from the same height to less than 3.0 percent variation from the computed theoretical free fall time.

Step Rating System. A step rating system has been devised by WADD to eliminate any unnecessary waste of cups and pins while seeking threshold values of test samples. This system sets 9 in. as the minimum drop height in which a sample, if necessary, should be tested and 48 in. as the maximum drop height. The height increment between two adjacent numbers is three inches. This three inch interval represents five foot-pounds of potential energy. No drops should be made at any level other than that corresponding to a three-inch increment.

Determination of Reaction. Determination of a reaction should be based on the following criteria an audible report, visible flash or any other evidence of a reaction upon post inspection of the striker pin at room temperature such as discoloration (charring) and pitting. The degree of severity of any reaction shall be classified as high, medium, low or char marks. If any reaction occurs on rebound, it should be reported and classified in accordance with the foregoing rating system.

Threshold Level. Whenever the operator observes zero reactions in twenty test drops at two adjacent heights that are three inches apart, the impact sensitivity threshold value of the material tested is the potential energy specified for the higher adjacent height. In seeking the threshold value of a sample, the first suggested test height is the 42-in. level.

Blank Tests. Blank specimen cups shall be tested to assure the operator that the specimen cups, striker pins and test area are sufficiently clean. The blank tests are made at the beginning of every 10 drops, and are always made from a drop height of 48 in.

Reports. The following data should be reported for each series of 20 test drops:

(1) The sample under investigation.

(2) The drop height of the plummet.

(3) The measured free fall time of the plummet and the computed theoretical free fall drop time for each drop height.

(4) The deviation of the average measured drop time from the theoretical free fall drop time in percent.

(5) Ambient temperature, humidity, barometric pressure and gravitational constant.

(6) Critical test parameters, the date, the laboratory, and the operator.

(7) Number of blank cups tested.

(8) The number and type of reactions observed.

D. Impact Sensitivity and Affiliated Test Results

During this contract period, twoimpact test programs involving test samples selected for the Cooperative Test Program No. 2 have been completed. The first program, the Pre-Cooperative Test Program No. 2, was conducted to determine the threshold values of three test samples initially selected for the Cooperative Test Program No. 2. The second program was the Cooperative Test Program No. 2 as requested by WADD. In addition, a program has been conducted to determine the threshold values of 16 selected liquid test samples in an attempt to find a fluid which may be used as a standard reference sample for the impact sensitivity test. Test results have been obtained on one grease sample, D-1094.

In an effort to improve the repeatability and reproducibility of the impact test, an investigation has been conducted on the variables that might affect the impact sensitivity of the samples. Affiliated impact tests have been made to determine the effects of sample thickness and sample floating on the sample sensitivity. Tests have been made with "dry" samples to attempt the elimination of the problem of sample cracking during freezing. On the basis of these investigations, repeatability tests have been made on several samples to check these theories.

1. Pre-Cooperative Test Program No. 2

The Pre-Cooperative Test Program No. 2 was conducted to determine the threshold values of three test samples initially selected for the Cooperative Test Program No. 2.

The test samples used for this program were blended at WADD and shipped to SwRI. The samples were blended by volume from two fluids as follows:

Sample Code	Percentage Blends
II-A	70% 4-11V Halocarbon 30% Ucon 65 LB
II-B	50% 4-11V Halocarbon 50% Ucon 65 LB
II-C	30% 4-11V Halocarbon 70% Ucon 65 LB

The test procedure and method of determining the threshold values were the same as those outlined in previous sections of this report except for the following details:

(1) The volume of test sample specified for each test specimen cup was 0.50 ± 0.02 ml.

(2) SwRI test specimen cups were used throughout the program.

(3) Additional tests were run at test heights not dictated by the reactions obtained.

A summary of the results obtained from this program is presented in Table 35. It will be noted that, except for the one series of tests on sample II-A at the 45-in. drop height, the results appear to be reasonable, and that a desirable spread of threshold values was obtained for the three samples. However, SwRI was advised, after the program was completed, that a chemical reaction between the two constituents of the three test samples had occurred some time after the samples were blended and that these test samples would not be used for the Cooperative Test Program No. 2.

TABLE 35. SUMMARY OF IMPACT TEST RESULTS OBTAINED FOR PRE-COOPERATIVE TEST PROGRAM NO. 2

Threshold Values Obtained: Test Sample II-A 21 in. (35 ft-lb)
Test Sample II-B 15 in. (25 ft-lb)
Test Sample II-C 9 in. (15 ft-lb)

Test Sample	Drop Hgt., in.	Number of Reactions per 20 Drops				
		Nature of Reactions				
		High	Medium	Low	Char	Total
II-A	45	0	0	0	4	4
	45	0	0	0	0	0
	42	0	0	0	3	3
	39	0	0	0	1	1
	36	0	0	1	1	2
	30	0	0	0	2	2
	24	0	0	0	3	3
	21	0	0	0	0	0
	18	0	0	0	0	0
II-B	42	1	0	0	0	1
	36	2	0	0	1	3
	21	0	0	0	2	2
	18	0	0	0	3	3
	15	0	0	0	0	0
II-C	42	3	1	2	0	6
	21	2	1	1	0	4
	15	1	0	2	0	3
	12	2	1	2	0	5
	9	0	0	0	0	0

SwRI specimen cups used with 0.50 ml of test sample.

2. Cooperative Test Program No. 2

As a result of the contradictory impact test results obtained in the WADD Cooperative Test Program No. 1[11.15], a meeting of the cooperative laboratories was held at WADD on February 16, 1959, and a tentative program was adopted for the Cooperative Test Program No. 2. The program was planned in an effort to establish an improved degree of correlation among the various impact testers currently being used to evaluate the compatibility of material with liquid oxygen. It was agreed that in this program additional parameters, such as the plummet weight, the striker pin area, and the test specimen cup, should be controlled more rigidly than those in the WADD Cooperative Test Program No. 1.

The Cooperative Test Program No. 2 was formally initiated by WADD[11.16] in March 1960. An oil blending procedure and a thorough test procedure, similar to the procedure outlined previously in this report, were included with the letter initiating the program. The two constituent fluids, necessary for blending the test samples, and the test specimen cups were supplied to all the cooperating laboratories by WADD. The striker pins and data sheets to be used for the program were distributed by SwRI on behalf of WADD.

The preparation of the test sample in this program was the same as in Pre-Cooperative Test Program No. 2, except that 0.47 ± 0.02 ml of test sample was specified. Although specifying a given volume of test sample does not assure a constant sample thickness when different test samples or cups from different sources are used, it should have no effect on the results from the Cooperative Test Program No. 2 since all cooperating laboratories used the same test samples with the same type of specimen cup.

Two fluids (11-14 Halocarbon, and Ucon 65 LB) were received from WADD. The three test samples were blended by volume from the two fluids supplied as follows:

Sample Code	Percentage Blends	Mixing Volumes
II-D	70% 11-14 Halocarbon	70 ml
	30% Ucon 65 LB	30 ml
		100 ml
II-E	50% 11-14 Halocarbon	50 ml
	50% Ucon 65 LB	50 ml
		100 ml
II-F	30% 11-14 Halocarbon	30 ml
	70% Ucon 65 LB	70 ml
		100 ml

Each sample was mixed just prior to tests and all tests on blended samples were to be completed within a period of two weeks from the day they were mixed. The mixed samples were kept in clean containers covered with aluminum foil to be shrouded from light. All glassware used in blending the samples was previously cleaned with a sulfuric acid-dichromate cleaning solution, rinsed with distilled water, and then air dried.

Each of the three test samples was tested at drop heights of 42, 30, 21, 15, 12, and 9 inches. A summary of the results obtained is presented in Table 36. It will be noted that the threshold value for sample II-D was determined to be 9 in. (15 ft-lb), and that no accurate threshold value was obtained for either sample II-E or II-F since reactions were obtained with both samples at 9 in. (15 ft-lb, the minimum recommended test height for this program). Therefore, the threshold values for both samples were reported as less than 9 in. (15 ft-lb). A plot of the number of reactions per 20 drops versus impact energy for each of the test samples is presented in Figure 50. It will be noted that the relative impact sensitivities of test samples II-E and II-F remain undefined when based only upon the number of reactions obtained per 20 drops at each test height. Although their threshold values or their relative impact sensitivities cannot be distinguished, fewer "Hi" and "Med" reactions were obtained for sample II-E than for sample II-F, as presented in the results in Table 36. It can therefore be concluded that sample II-E is less reactive than sample II-F when based upon the number and the nature of the reactions obtained.

In an effort to provide a method of analysis which may afford a more complete means of rating the impact sensitivities of the three test samples selected for Cooperative Test Program No. 2, the following "reaction rating" method has been devised. This method of analysis is based upon the number as well as the nature of reactions per 20 drops. A "reaction rating number" is assigned to each of the different types of reactions as follows:

Nature of Reaction	Reaction Rating Number
High	4
Medium	3
Low	2
Char	1
None	0

A sum of the 20 reaction rating numbers, obtained for each test sample at each energy level tested, is taken to obtain the reaction rating for that test sample at that energy level. If all the test samples are tested at exactly the same energy levels, a sum of their respective reaction ratings will provide

TABLE 36. SUMMARY OF IMPACT TEST RESULTS OBTAINED FOR COOPERATIVE TEST PROGRAM NO. 2

Threshold Values Obtained: Test Sample II-D 9 in. (15 ft-lb)
Test Sample II-E <9 in. (<15 ft-lb)
Test Sample II-F <9 in. (<15 ft-lb)

Test Sample	Drop Hgt., in.	Number of Reactions per 20 Drops: Nature of Reactions: High	Medium	Low	Char	Total
II-D	42	0	0	0	3	3
	30	0	0	0	5	5
	21	0	0	0	1	1
	15	0	0	0	2	2
	12	0	0	1	2	3
	9	0	0	0	0	0
II-E	42	2	1	2	3	8
	30	0	1	1	8	10
	21	0	1	2	3	6
	15	0	0	0	5	5
	12	0	0	2	1	3
	9	0	0	0	2	2
II-F	42	2	3	1	6	12
	30	2	2	2	3	9
	21	1	1	2	2	6
	15	2	0	1	4	7
	12	0	0	1	1	2
	9	1	1	1	0	3

WADD specimen cups used with 0.47 ml of test sample.

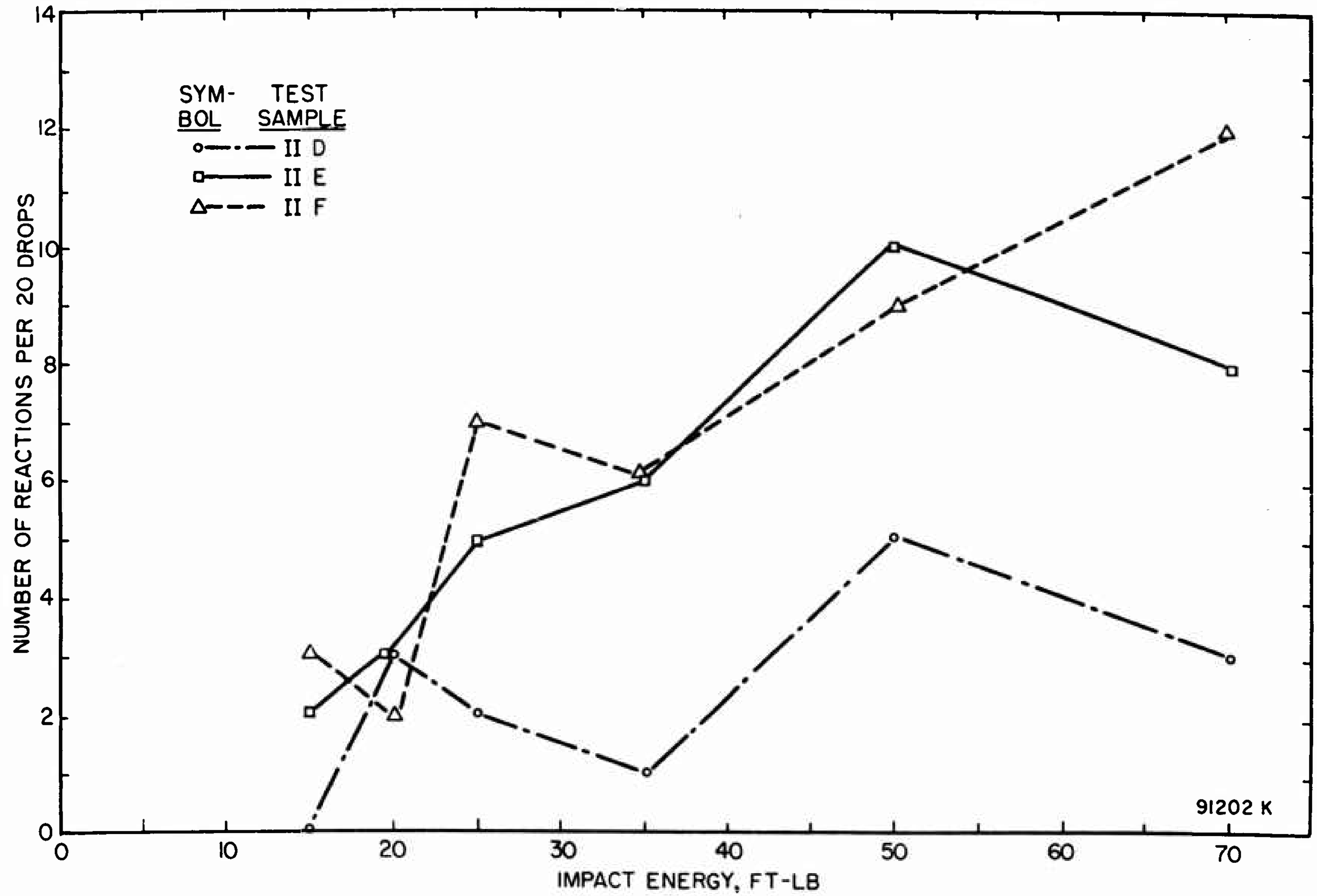


FIGURE 50. IMPACT SENSITIVITY CURVES FOR COOPERATIVE TEST PROGRAM NO. 2 TEST SAMPLES

a "total reaction rating" which may be compared numerically. The larger the total reaction rating is numerically, the more reactive the test sample has performed during the tests.

Table 37 presents an example of the application of this rating method as it is applied to the SwRI results for Cooperative Test Program No. 2. It will be noted that the suggested method rates test sample II-D as the least reactive test sample and II-F as the most reactive test sample. Figure 51 presents a plot of the total reaction rating number versus percent Ucon 65 LB for the three test samples. It appears from these data that a linear relationship exists between the percentage of Ucon 65 LB in the test samples and the total reaction rating. Figure 52 presents a plot of reaction rating versus impact energy. Comparing this plot with Figure 50, it will be noted that the reaction rating method provides a somewhat better separation of the impact sensitivity curves for the different samples, indicating that this method of analysis may provide a suitable means of rating the impact sensitivities of different test samples even though their threshold values are the same.

3. Determination of Threshold Values of Submitted Test Samples

A test program has been conducted during this contract period to determine the threshold values of sixteen selected fluid samples. These samples were selected by WADD and were tested in an attempt to find a fluid which may be used in the future as a standard reference sample for the impact sensitivity test. For an ideal reference sample fluid, the fluid should have a medium threshold value (near 30 in., or 50 ft-lb), a stable threshold value during storage, and a resistance to excessive floating after being frozen in the specimen cup.

Tests on these sixteen sample fluids were completed and a summary of the test results is presented in Table 38. Summary tables of the individual test sample results are presented in Appendix V (Tables 68 to 84). By comparing the test results of these sample fluids with the desired qualifications of a reference fluid, three of the fluids have been selected as tentative reference fluids. These three fluids, CG-18, CG-35, and D-1093 have threshold values of 12 in., 21 in., and 30 in. respectively; they can be easily measured and do not crack excessively or float in liquid oxygen after being frozen. Two of the tentative reference fluids, CG-18 and CG-35 have been used in subsequent test programs and their performance in these respects was satisfactory.

The medium threshold value of 33 in. obtained during the first series of tests with sample D-1066 satisfies the requirement of a standard reference fluid. However, no reactions were obtained at 42 in. and 36 in.

TABLE 37. SUMMARY OF IMPACT TEST RESULTS OBTAINED FOR COOPERATIVE TEST PROGRAM NO. 2 USING REACTION RATING METHOD

Test Sample	Drop Hgt., in.	Number of Reactions per 20 Drops: Nature of Reactions: High	Medium	Low	Char	Total	Reaction Rating
II-D	42	0	0	0	3	3	3
	30	0	0	0	5	5	5
	21	0	0	0	1	1	1
	15	0	0	0	2	2	2
	12	0	0	1	2	3	4
	9	0	0	0	0	0	0
						Total	15
II-E	42	2	1	2	3	8	18
	30	0	1	1	8	10	13
	21	0	1	2	3	6	10
	15	0	0	0	5	5	5
	12	0	0	2	1	3	5
	9	0	0	0	2	2	2
						Total	53
II-F	42	2	3	1	6	12	25
	30	2	2	2	3	9	21
	21	1	1	2	2	6	13
	15	2	0	1	4	7	14
	12	0	0	1	1	2	3
	9	1	1	1	0	3	9
						Total	85

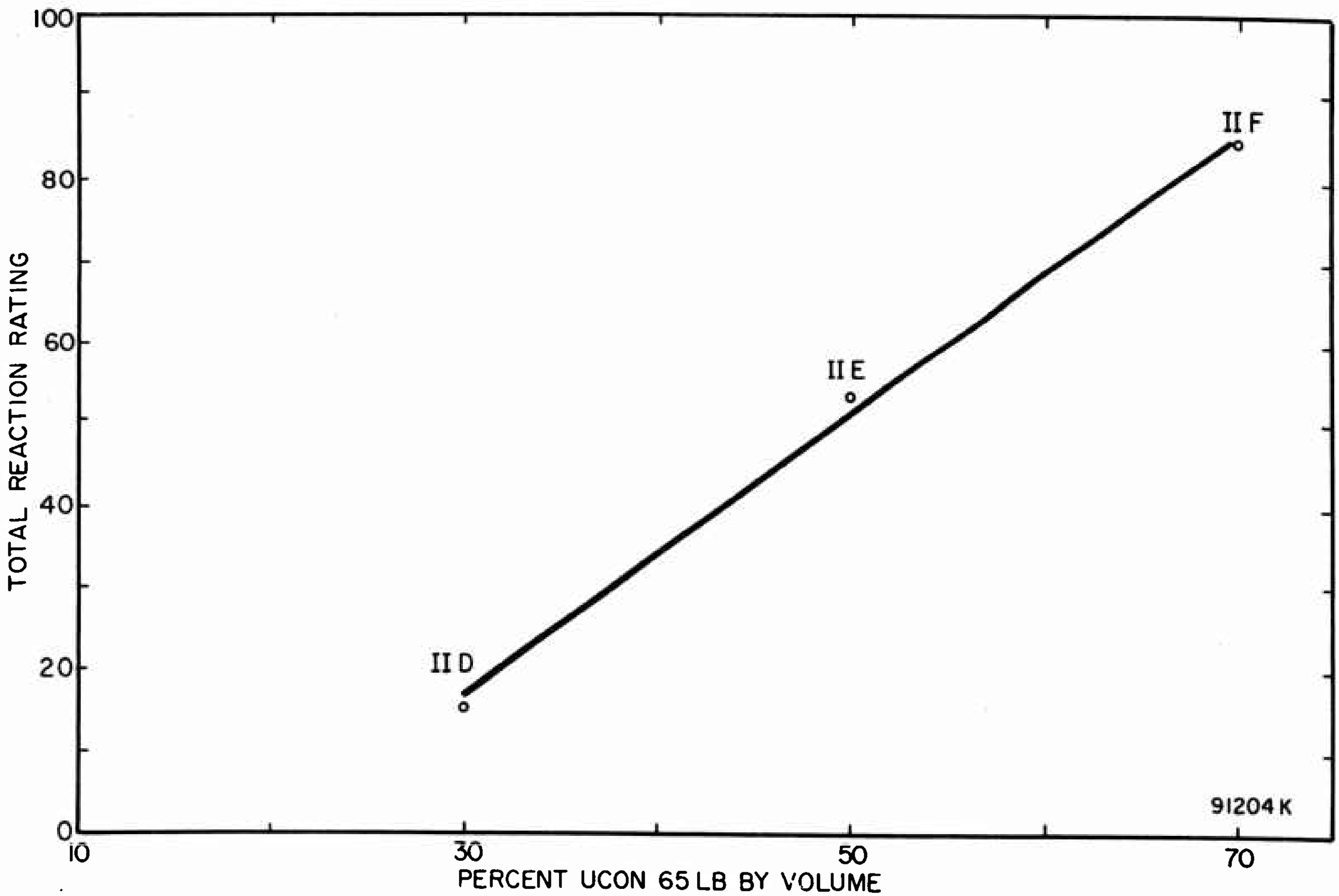


FIGURE 51. EFFECT OF INCREASED PERCENTAGES OF UCON 65 LB ON THE TOTAL REACTION RATING FOR COOPERATIVE TEST PROGRAM NO. 2 TEST SAMPLES

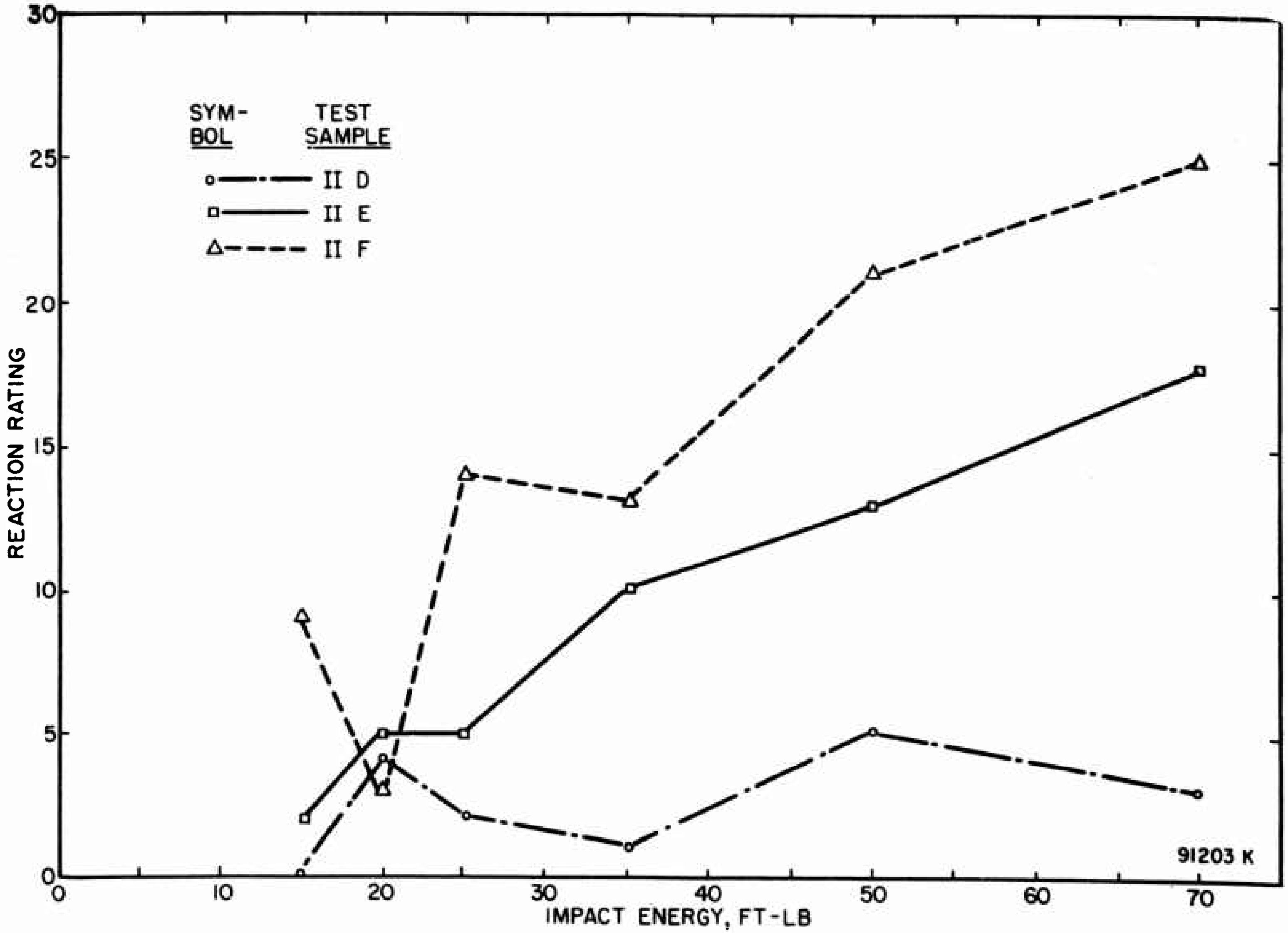


FIGURE 52. REACTION RATING CURVES FOR COOPERATIVE TEST PROGRAM NO. 2 TEST SAMPLES

TABLE 38. SUMMARY OF THRESHOLD VALUE DETERMINATIONS FOR SIXTEEN DIFFERENT FLUID SAMPLES

Test Sample	Description	Threshold Value: Height, in.	Threshold Value: Potential Energy, ft-lb
CG-5	Chlorinated Phenyl Silicone	<9	<15
CG-9	Silphenylene (1958)	9	15
CG-18	Di-2-Ethylhexyl Azelate	12	20
CG-26	Halogenated Oil	>45	>75
CG-32	Pentaerythritol Ester	<21	<35
CG-34	Chlorinated Methyl Phenyl Silicone	9	15
CG-35	Inhibited Methyl Phenyl Silicone	21	35
CG-58	Pentaerythritol Ester	<21	<35
CG-59	Pentaerythritol Ester	<21	<35
CG-60	Phenyl Silicone	<21	<35
CG-61	Bis (Phenoxy Phenoxy) Benzene	<9	<15
CG-62	Silphenylene (1960)	12	20
CG-63	Trimethylpelorgonate Ester	<21	<35
D-1060	Nitrile Silicone	<21	<35
D-1066 (1st Series)	(Not available)	33	55
D-1066 (2nd Series)	(Not available)	>42	>70
D-1071	(Not available)	>45	>75
D-1093		30	50

drop heights during the second series of tests on the same fluid. The fact that all the reactions observed in the first series of tests occurred on rebounds has complicated the evaluation of the threshold value for this fluid. Before the question as to whether rebounds should be counted as positive reactions or not is determined, it appears that the threshold value of this sample cannot be accurately determined.

The grease sample testing procedure,[11, 17] especially the grease sample preparation, has been practiced and tests on one grease sample, designated D-1094, were completed. The results of these tests are presented in Table 39.

It has been found that if a strip of 0.002-in. aluminum foil was placed in the channel of the sample leveling slab, and the disc-shaped samples were cut with the sample cutter before the samples were completely frozen, the problem of cracking of the samples was minimized and the frozen samples could be detached from the slab without difficulty. During the testing process, only a small amount of liquid oxygen was allowed in the specimen cups with the frozen samples when they were being transferred from the cooling pan to the specimen cup holder. An excessive amount of liquid oxygen would cause the frozen grease samples to float up in the liquid oxygen and it would be quite difficult to place the striker pins on top of the frozen samples in the correct position.

4. Effect of Sample Thickness on Impact Sensitivity of Samples

During tests in Cooperative Test Program No. 2, it was strongly felt that the sample thickness, to some extent, affects the results of the impact test. Theoretically, the impact energy absorbed per unit volume of sample under the impact area of the striker pin will be increased if the total impact energy remains constant and the sample thickness is reduced. Therefore, a program was initiated to investigate the effect of sample thickness on sample sensitivity under impact and in the presence of liquid oxygen.

Two fluid samples, CG-35 and CG-18, with sample thicknesses of 0.020 in., 0.040 in. and 0.060 in. were used in the tests. At first a sample thickness of 0.010 in. was used, but due to the extreme thinness of the sample, the frozen sample floated very easily in the liquid oxygen. Out of approximately 34 samples prepared, only 3 or 4 could be used after being frozen and topped with liquid oxygen. For this reason the 0.010 in. thickness was not used in the tests. Twenty drops were made with each of the three sample thicknesses at drop heights of 42, 30, and 21 inches. Summaries of the test results are presented in Tables 40 and 41 for samples CG-18 and CG-35 respectively. The total number of reactions per 20 drops are plotted versus sample thickness for CG-18 and CG-35 in Figures 53 and 54. It will

TABLE 39. SUMMARY OF IMPACT TEST RESULTS ON GREASE SAMPLE D-1094 WITH LOX

Threshold Value Determined: <12 in. (20 ft-lb)

Test Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			**Blank tests**
1	42	20	13	6 high explosions 3 medium explosions 4 low explosions	
	48	2			Blank tests
2	21	20	6	1 high explosion 5 low explosions	
	48	2			Blank tests
3	12	20	2	1 medium explosion 1 low explosion	

Test sample thickness 0.050 in.

TABLE 40. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-18 TO DETERMINE THE EFFECT OF SAMPLE THICKNESS ON IMPACT SENSITIVITY

Sample Thickness, in.	Oil Volume, ml	Drop Hgt., in.	No. of Tests	No. of Reactions				
				High	Med	Low	Char	Total
0.020	0.34	21	20	4	-	-	-	4
	0.34	30	20	4	1	-	-	5
	0.34	42	20	10	2	-	-	12
0.040	0.54	21	20	1	1	-	-	2
	0.54	30	20	-	-	1	-	1
	0.54	42	20	-	1	3	-	4
0.060	0.76	21	20	-	-	-	-	0
	0.76	30	20	-	1	-	-	1
	0.76	42	20	1	1	-	-	2

TABLE 41. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-35 TO DETERMINE THE EFFECT OF SAMPLE THICKNESS ON IMPACT SENSITIVITY

Sample Thickness, in.	Oil Volume, ml	Drop Hgt., in.	No. of Tests	No. of Reactions				
				High	Med	Low	Char	Total
0.020	0.26	21	20	-	3	-	-	3
	0.26	30	20	6	-	3	1	10
	0.26	42	20	8	1	1	-	10
0.040	0.48	21	20	-	-	-	-	0
	0.48	30	20	-	-	-	-	0
	0.48	42	20	-	-	-	1	1
0.060	0.66	21	20	-	-	-	-	0
	0.66	30	20	-	-	2	-	2
	0.66	42	20	2	-	-	-	2

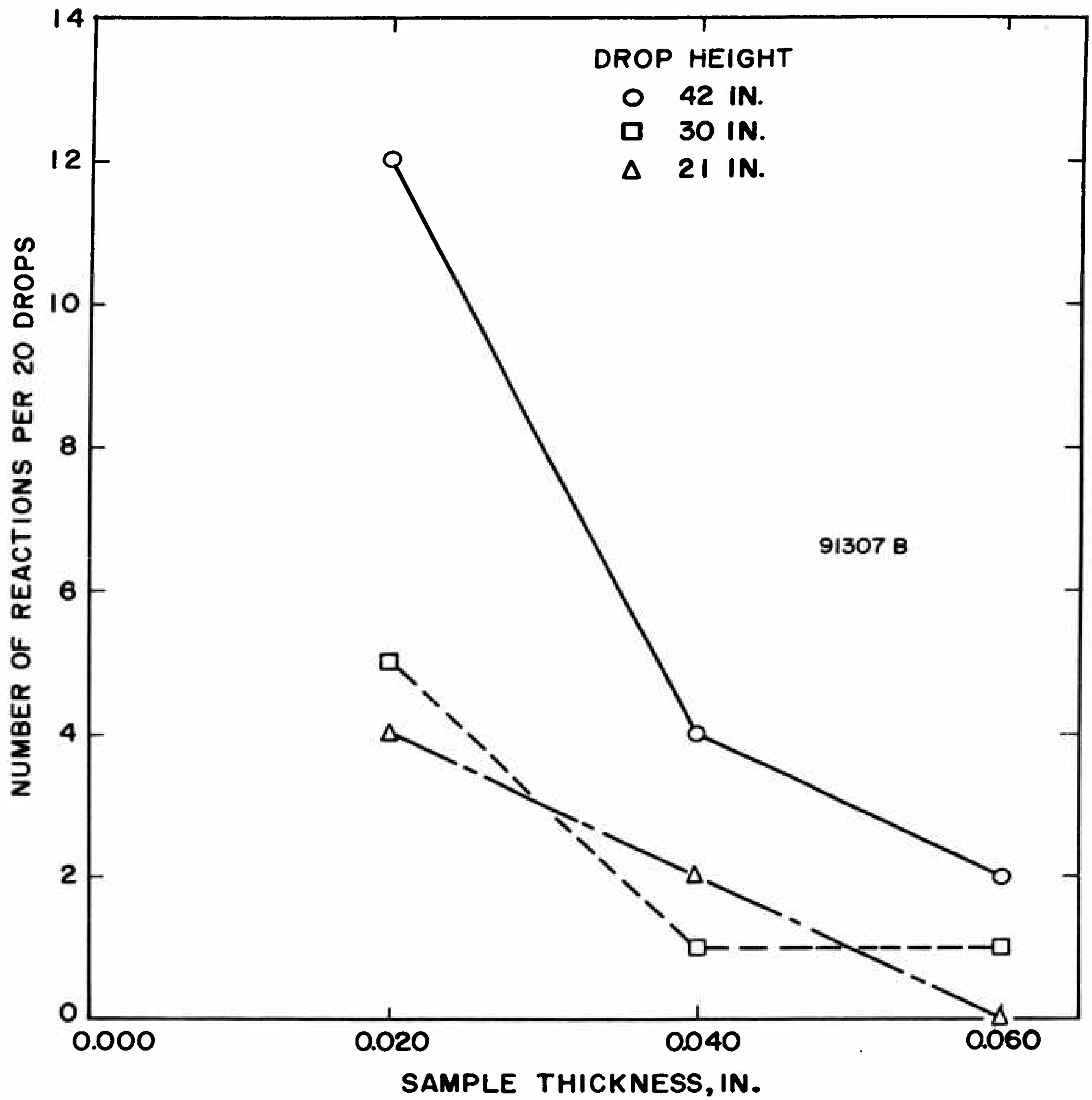


FIGURE 53. EFFECT OF SAMPLE THICKNESS ON THE NUMBER OF REACTIONS PER 20 DROPS FOR SAMPLE CG-18

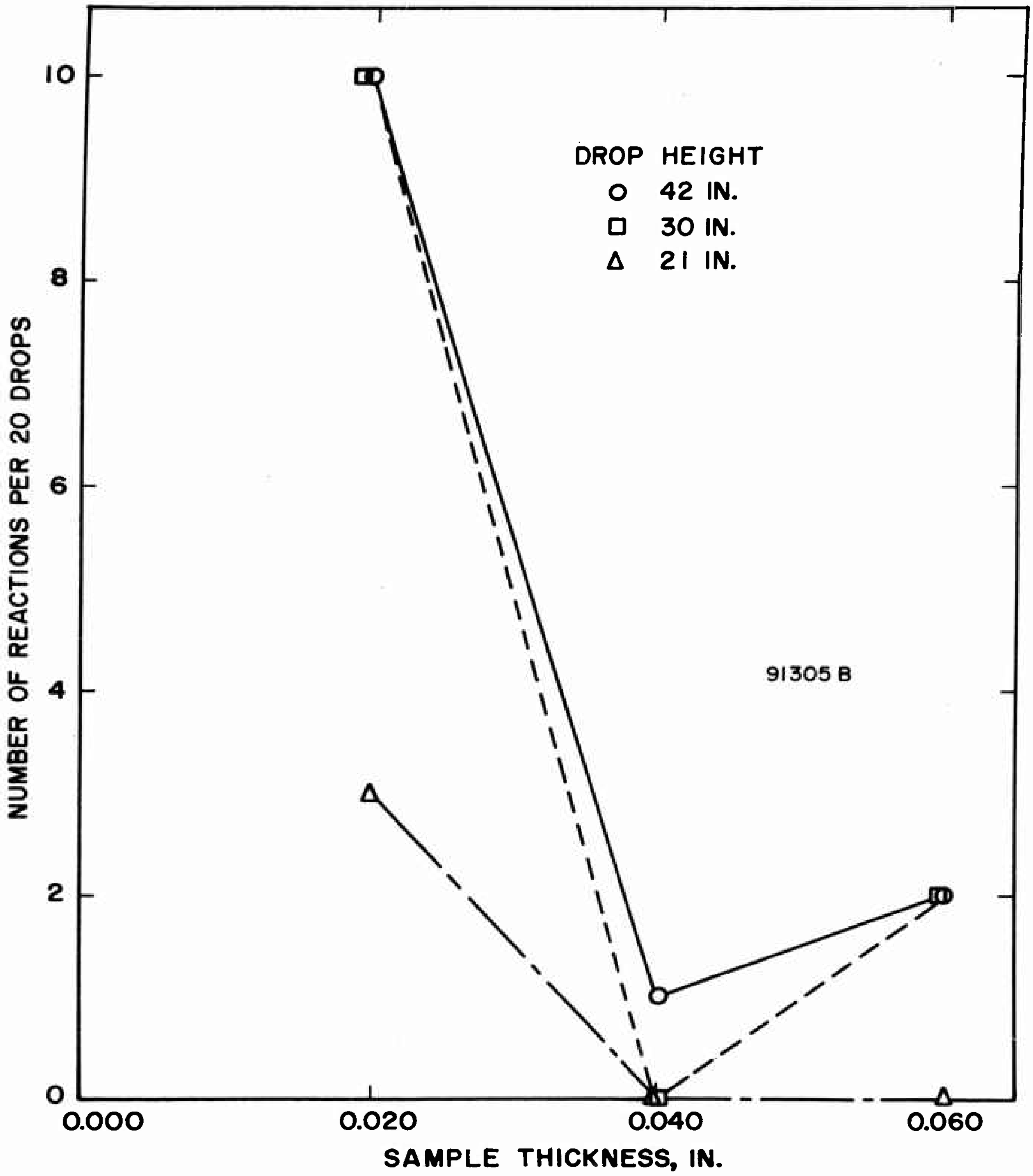


FIGURE 54. EFFECT OF SAMPLE THICKNESS ON THE NUMBER OF REACTIONS PER 20 DROPS FOR SAMPLE CG-35

be noted that in general, when the sample thickness was decreased from 0.060 to 0.040 in., there was only a small change in the sensitivity of the sample. However, when the sample thickness was further decreased from 0.040 to 0.020 in., the sensitivity increased considerably. In the impact sensitivity tests, it is desirable that the sample thickness is such that a small variation from the specified thickness will not affect the sensitivity considerably. Therefore, it appears that sample thicknesses between 0.040 and 0.060 in. are satisfactory for this purpose. On the other hand, it has been proven that the sample thickness does affect, to some extent, the results of the impact test. It should be remarked that the standard sample thickness of 0.050 in. has been fully justified by the results obtained in the program.

5. Effect of Sample Floating on Impact Sensitivity

One of the problems encountered in preparing the sample for impact test has been the floating of the frozen samples in the liquid oxygen. During the process of precooling the samples to the liquid oxygen temperature, the samples in the specimen cups will invariably develop cracks, but will usually maintain a relatively smooth surface. When liquid oxygen is poured into the cups containing the frozen samples, some of the frozen samples may separate from the bottom of the specimen cup and float in the liquid oxygen, leaving a void spot in the frozen samples. The area of the void spot varies from a small speck or gap to almost half of the frozen sample surface. Sometimes the entire frozen sample will crack into small pieces and float in the liquid oxygen. These floated samples are normally discarded, and additional samples are prepared if necessary. However, in order to determine what effect floated samples might have on the impact test results, comparative data were obtained with floated samples using two test fluids, CG-18 and CG-35, which had previously been tested using normal samples.

Sample thicknesses of 0.040 in. and 0.060 in. were used in the floated sample tests of these two sample fluids. Table 42 presents a comparison of the test results with normal and floated samples on sample fluids CG-18 and CG-35. The total number of reactions in 20 test drops made with the floated and normal samples at different sample thicknesses are plotted versus the drop heights in Figures 55 and 56 for the two sample fluids. From these results, it will be noted that a larger number of reactions was generally obtained with the floated samples than with the normal samples. It is believed that with the floated samples, the amount of frozen sample under the striking area of the striker pin is generally less than in the case of normal sample; this excludes, of course, the possibility that there is no sample at all under the pin. Consequently, when the striker pin transmits the impact energy of the plummet to the frozen sample, the impact energy absorbed by the sample per unit volume will be greater in the case of floated samples. As has been demonstrated in the tests on the effect of sample thickness on sample sensitivity,

TABLE 42. COMPARISON OF IMPACT TEST RESULTS WITH NORMAL AND FLOATED SAMPLES ON CG-18 AND CG-35

Sample Thickness, in.	Oil Volume, ml	Drop Hgt., in.	No. of Tests	No. of Reactions	
				Normal	Floated
CG-18					
0.040	0.54	12	20	0	6
	0.54	21	20	2	6
	0.54	30	20	1	7
	0.54	42	20	4	6
0.060	0.76	12	20	0	3
	0.76	21	20	0	6
	0.76	30	20	1	4
	0.76	42	20	2	1
CG-35					
0.040	0.48	12	20	0	1
	0.48	21	20	0	3
	0.48	30	20	0	6
	0.48	42	20	1	8
0.060	0.66	12	20	1	1
	0.66	21	20	0	1
	0.66	30	20	2	1
	0.66	42	20	2	3

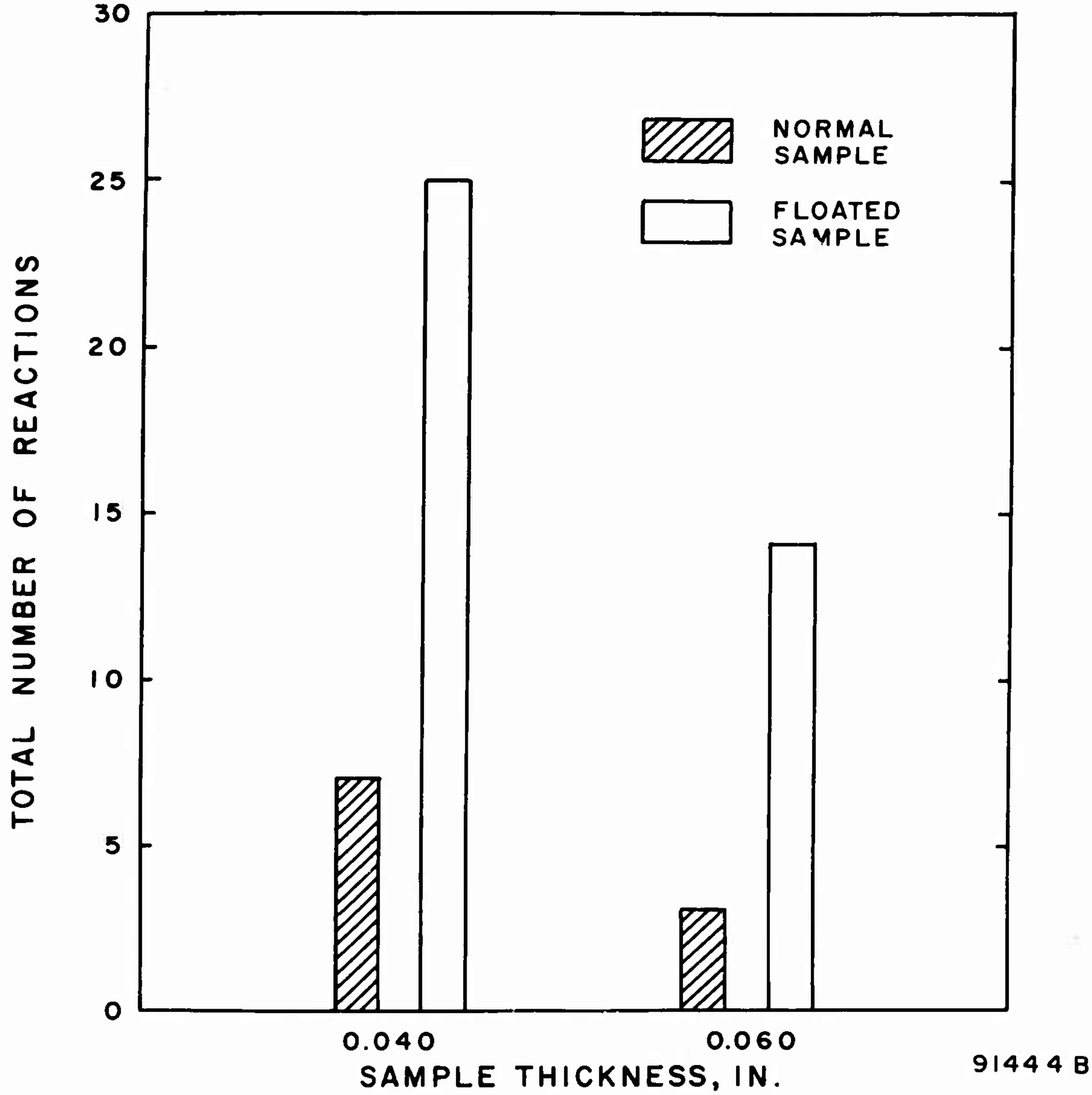


FIGURE 55. EFFECT OF SAMPLE FLOATING ON IMPACT SENSITIVITY OF SAMPLE CG-18

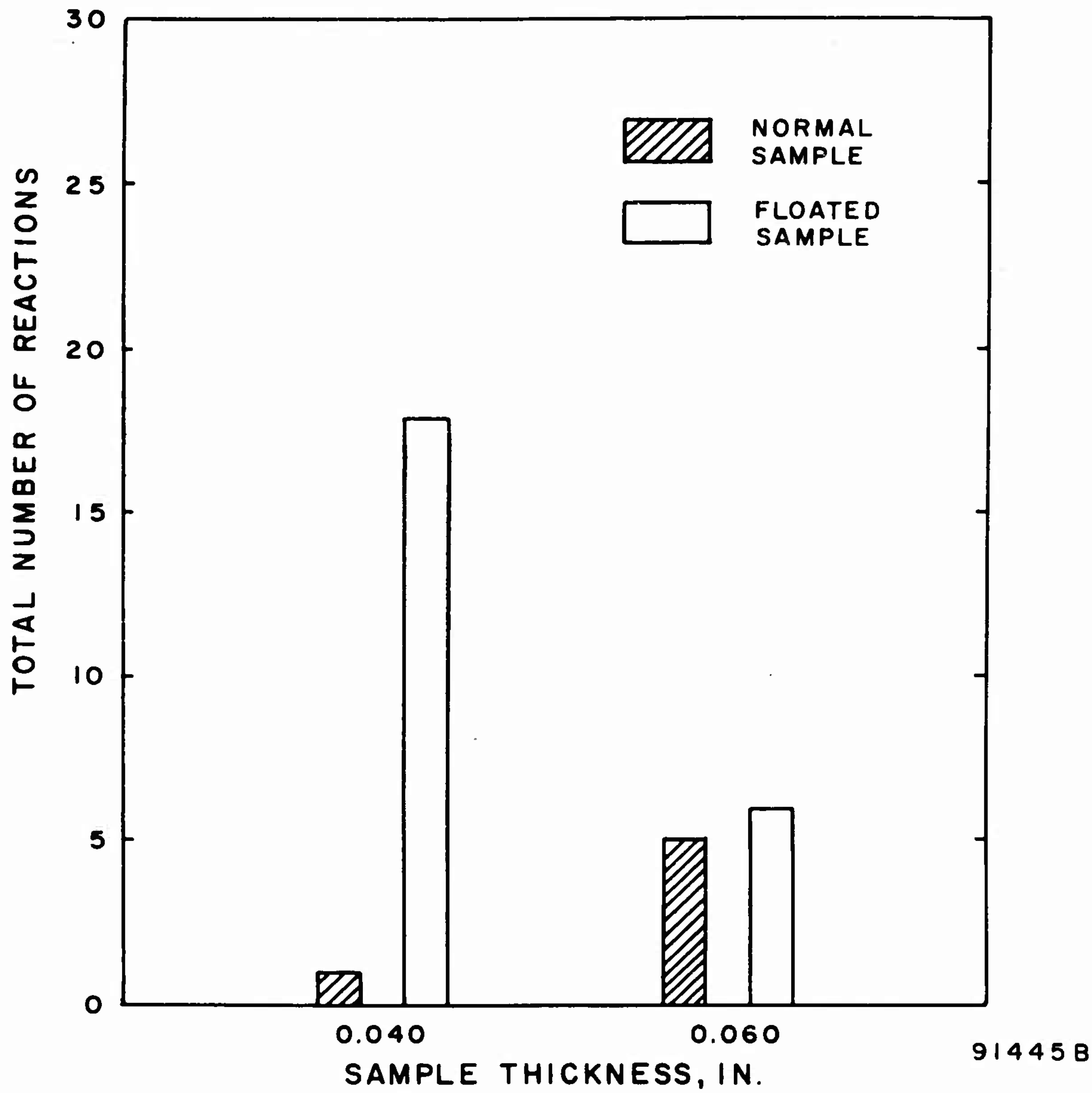


FIGURE 56. EFFECT OF SAMPLE FLOATING ON IMPACT SENSITIVITY OF SAMPLE CG-35

the increase in the energy absorbed per unit volume of the sample will in turn increase the sensitivity of the sample, i. e., the number of reactions per 20 drops.

Since different sample fluids appear to exhibit varied degrees of sample floating, and these degrees of floating are further affected by other factors such as the method of cooling, etc., it is believed that this variable indeed has an important role in affecting the impact test results.

6. Impact Test Results on "Dry" Samples

As a first attempt to eliminate the possibility of sample floating, tests have been made on two sample fluids, CG-18 and CG-35, using a slightly different method of sample preparation. Instead of putting liquid oxygen in the specimen cups after the samples have been frozen in the precooling pan, the "dry" frozen samples were placed in the specimen cup holder, the pre-cooled striker pins were placed on the frozen surface and then liquid oxygen was put in the specimen cups. The reason for following this procedure was that by having the weight of the pins on the frozen samples, they will not float when liquid oxygen is added to the cup and thereby a constant volume of sample can be maintained under the striking area of the pins.

Prior to the tests on these "dry" samples, preliminary experiments were conducted to insure that the "dry" frozen samples in the specimen cup would not soften to the extent that the striker pin would sink into the sample before liquid oxygen was poured into the specimen cup. The average time was measured from the moment the precooled "dry" sample was placed in the specimen cup holder to the moment the frozen sample started to melt. It was found that the "dry" sample could maintain its frozen state for an average of 28 seconds before starting to melt. This period of time was quite sufficient to allow the operator to finish the other necessary procedure steps before pouring the liquid oxygen into the specimen cup. In addition to this, the precaution was also taken to examine the frozen surface of several samples after the striker pin was placed in position and allowed to set in position for approximately 18 seconds. Particular attention was paid with respect to the possible indent of the striker pin on the frozen surface. No trace of striker pin indentation was observed and the frozen sample surface appeared to be satisfactory.

The results of the impact tests on "dry" samples are compared with the results of tests on normal samples for sample fluids CG-18 and CG-35 in Table 43. It will be noted that the threshold values obtained with the "dry" samples were higher than those obtained with the normal samples for both sample fluids. However, the repeatability of the tests using "dry" samples is yet to be determined.

TABLE 43. COMPARISON OF IMPACT TEST RESULTS WITH "DRY" AND NORMAL SAMPLES ON CG-18 AND CG-35

Drop Hgt., in.	Normal Samples No. of Tests	Normal Samples No. of Reactions	"Dry" Samples No. of Tests	"Dry" Samples No. of Reactions
CG-18				
42	6	1	20	1
36	--	--	20	1
30	--	--	20	7
21	3	1	20	0
15	4	1	--	--
12	20	0	20	0
9	20	0	--	--
Threshold Value	12 in.		21 in.	
CG-35				
42	5	1	20	3
39	17	2	20	2
36	29	1	20	0
33	23	2	20	1
30	23	1	--	--
27	7	1	--	--
24	3	1	--	--
21	20	0	20	0
18	20	--	--	--
Threshold Value	21 in.		<33 in., >21 in.	

7. Repeatability of Threshold Value Determinations

Repeatability tests were conducted on several sample fluids whose threshold values had been determined previously. For those samples that appear to remain stable in storage, the results obtained have been quite satisfactory. Table 44 presents a summary of impact test data showing the repeatability of threshold values for sample fluids CG-26, CG-35 and D-1093. It will be noted that the maximum deviation in threshold values for each respective fluid was 3 in. drop height or 5 ft-lb impact energy.

In reviewing the results obtained in these repeatability tests, it is of particular interest that all three fluids, CG-26, CG-35 and D-1093, did not crack excessively nor float easily when liquid oxygen was added during the precooling procedure. In fact, it was quite difficult to obtain floated samples on sample CG-35 during the tests made with floated samples.

E. Conclusions

In view of the test results obtained in the various programs during this contract period, especially in the repeatability test results, it was concluded that the ABMA impact tester, with the minor modifications made by WADD and SwRI, and the standardized test procedure (tentative) used with this tester, are basically sound and satisfactory for the determination of the impact sensitivity of lubricants in contact with liquid oxygen.

Due to the varying test sample thicknesses obtained when using equal volumes of different test samples in the same specimen cups, it was concluded that all future impact sensitivity tests should be conducted using a specified test sample thickness. Also, in view of the data obtained on the effect of sample thickness on sample sensitivity, it was further concluded that since only a relatively small difference in sample sensitivity was noted when the sample thickness was reduced from 0.060 to 0.040 in., the standard sample thickness of 0.050 in. has been fully justified and is satisfactory for use in future impact test programs.

It was concluded that 17-4PH stainless steel should be used as the material for future standard striker pins after ascertaining that the durability, machinability and corrosion resistance properties of this material are equal to or superior to those properties of the other materials tested.

Certain factors affecting the sensitivity of a test sample remain to be eliminated, or at least minimized, among which sample cracking and floating during the sample precooling process currently appear to play an important role.

TABLE 44. SUMMARY OF IMPACT TEST DATA SHOWING REPEATABILITY OF THRESHOLD VALUES

Sample: CG-35

Drop Hgt., in.	Ratio of No. of Reactions to No. of Test Drops		
	May 1960	June 1960	October 1960
24	1/3	1/4	1/8
21	0/20	1/14	0/20
18	0/20	0/20	0/20
Threshold Value, in.	21	18	21
Threshold Value, ft-lb	35	30	35

Sample: D-1093

Drop Hgt., in.	Ratio of No. of Reactions to No. of Test Drops	
	September 1959	November 1960
42	1/8	1/6
36	1/11	1/8
30	1/9	0/20
27	0/20	0/20
Threshold Value, in.	27	30
Threshold Value, ft-lb	45	50

Sample: CG-26

Drop Hgt., in.	Ratio of No. of Reactions to No. of Test Drops	
	June 1960	October 1960
42	0/20	0/20
Threshold Value, in.	>42	>42
Threshold Value, ft-lb	>70	>70

In view of the results of the Cooperative Test Program No. 2 from all of the cooperating laboratories*, it is recommended that a Cooperative Test Program No. 3 be initiated in an effort to establish a correlation of the results obtained with impact testers used by various laboratories to evaluate the compatibility of materials in contact with liquid oxygen.

*The results of the Cooperative Program No. 2 were distributed to all cooperating laboratories by WADD leter dated 8 November 1960.

BIBLIOGRAPHY

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The following is a complete list of SwRI reports on lubrication and related research and test method development for aviation propulsion systems, issued over the period of April 1, 1953 to January 15, 1961, under contracts AF 33(616)-498, AF 33(616)-2659, AF 33(616)-3820, AF 33(616)-6232, and AF 33(616)-7223.

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APPENDIX I

CHARACTERISTICS OF TEST FLUIDS

TABLE 45. CHARACTERISTICS OF TEST FLUIDS

Oil Code	Viscosity, cs		Gear Rating, lb/in.(a)	Engine Test						Remarks
	100°F	210°F		Oil-In Temp, °F	Time, hr	Viscosity (100°F) at End of Test, cs	Coke(b)	Sludge(b)	Pass	
GTO-313	17.1	4.61	2250	-	100	16.31	F	G	Pass	MIL-L-7808C
GTO-770	64.6	10.93	4400	-	-	-	-	-	-	MIL-L-9236A type
GTO-790	27.3	5.17	2480	400	20	91	-	-	Fail	MIL-L-9236A type
GTO-794	34.5	7.31	3140	400	20	221	-	-	Fail	MIL-L-9236A type
GTO-803	34.4	7.03	2910	-	-	-	-	-	-	Different batch of GTO-794
GTO-855	29.0	5.30	2230	400	30	132	-	-	Fail	MIL-L-9236A type
GTO-861	15.5	3.55	2080	-	-	-	-	-	-	MIL-L-9236B type
GTO-882	15.1	-	1900	425	100	27.7	VG	VG	Pass	MIL-L-9236B type
GTO-885-1	15.5	3.55	1970	425	100	19.8	G	G	Pass	Different batch of GTO-861
GTO-915	16.0	3.61	1820	-	-	-	-	-	-	Different batch of GTO-861
GTO-939	15.1	3.47	-	-	-	-	-	-	-	Different batch of GTO-882
GTO-950	-	-	-	-	-	-	-	-	-	Different batch of GTO-861
LRO-8	75.5	6.41	-	-	-	-	-	-	-	Polyphenyl ether 4P3E mixed isomers
LRO-11	70.9	6.32	-	-	-	-	-	-	-	Polyphenyl ether 4P3E mixed isomers
LRO-12	395.3	-	-	-	-	-	-	-	-	Polyphenyl ether 5P4E mixed isomers
LRO-13	368.0	13.21	-	-	-	-	-	-	-	Polyphenyl ether 5P4E mixed isomers
Ref "B"	237.8	20.3	2720	-	-	-	-	-	-	Mineral oil, Grade 1100, MIL-L-6082
C-1003	39.4	5.80	740	-	-	-	-	-	-	Mineral oil, USP Grade, white
0-58-24	34.7	-	-	-	-	-	-	-	-	Different batch of GTO-794
0-59-26	18.7	-	-	-	-	-	-	-	-	MIL-L-9236B type
0-60-11	21.2	-	-	-	-	-	-	-	-	MIL-L-9236B type
0-60-12	16.1	-	-	-	-	-	-	-	-	MIL-L-9236B type
0-60-13	25.7	-	-	-	-	-	-	-	-	Different batch of GTO-790
0-60-23	16.0	3.63	-	-	-	-	-	-	-	Different batch of GTO-861
0-60-26	15.0	3.46	-	-	-	-	-	-	-	Different batch of GTO-882
0-60-27	15.0	3.45	-	-	-	-	-	-	-	Different batch of GTO-882

(a) Standard Ryder gear test (165°F) except that WADD high-temperature gear machine was used.
(b) VG = Very Good, G = Good, and F = Fair.

APPENDIX II

STATISTICAL ANALYSIS OF 85-MM BEARING FATIGUE DATA

STATISTICAL ANALYSIS OF 85-MM BEARING FATIGUE DATA

The following is an explanation of the method of analysis[11, 18] employed in comparing the 85-mm bearing constant-load and step-load fatigue data obtained during this report period. The data used in this example is for the Weibull plot shown in Figure 35.

Equivalent Fatigue Life

The equivalent fatigue life for a bearing tested to failure by the step-load procedure is given by.

$$L_F = L_{F_1}\left(\frac{P_1}{P}\right)^3 + L_{F_2}\left(\frac{P_2}{P}\right)^3 + L_{F_3}\left(\frac{P_3}{P}\right)^3$$

From Table 23, bearing 2-C-2 was subjected to 50 hours at 9785 lb, 50 hours at 13,430 lb, and then run at 16,940 lb for 12 hours at which point the bearing failed. The equivalent constant load (P = 9785 lb) life for this bearing is

$$L_F = 50\left(\frac{9785}{9785}\right)^3 + 50\left(\frac{13,430}{9785}\right)^3 + 12\left(\frac{16,940}{9785}\right)^3 = 209.4 \text{ hrs}$$

The balance of the data for each bearing is calculated in the manner shown above. These equivalent life values are the abscissae for Figure 35.

Median Rank

A median rank is assigned to each bearing's equivalent life.[11, 18] These ranks vary depending upon the sample size, n, and serve as the ordinates for Figure 35.

Weibull Plot

The six sets of coordinates are now plotted on a special probability paper of the logarithm of the life versus log 1/1 - F where F is the median rank. Since this type of plot will result in a straight line, the "method of

least squares" (11.19) is used to determine the line's exact location and slope.

<u>90% Confidence Band</u>

From other tables(11.18), 95 percent and 5 percent ranks are obtained for a particular sample size and are substituted in the ratios

$$\left(\frac{\ell n \dfrac{1}{1 - z_{.95}}}{\ell n \dfrac{1}{1 - z_{.05}}}\right)^{1/2b} = A\;; \qquad \left(\frac{\ell n \dfrac{1}{1 - z_{.05}}}{\ell n \dfrac{1}{1 - z_{.95}}}\right)^{1/2b} = B$$

where $z_{.95}$ and $z_{.05}$ are 95 percent and 5 percent ranks, respectively, and b is the Weibull slope.

The quantities A and B are then multiplied by corresponding Central Values (fatigue life on the constructed Weibull plot for the particular median rank of each bearing) to obtain Upper and Lower Limits for the Weibull plot. These limits are dual abscissae for each Central Value, and are then plotted on the Weibull probability paper to complete Figure 35.

<u>Mean Life</u>

From Figure 57, the "percent failed at the mean" is obtained for the Weibull plot. For Figure 35 (slope = 1.48) the percent failed at the mean is 57.6 percent which corresponds to a Mean Life of 1100 hours.

<u>Mean Life Ratio</u>

To compare constant and step-load Weibull plots (Figures 31 and 35), their "mean life ratio" is calculated from the ratio

$$MLR = \frac{\text{Mean Life of Step-Load Plot}}{\text{Mean Life of Constant-Load Plot}}$$

where the Mean Life of the Constant-Load Plot is obtained in the same manner as described above.

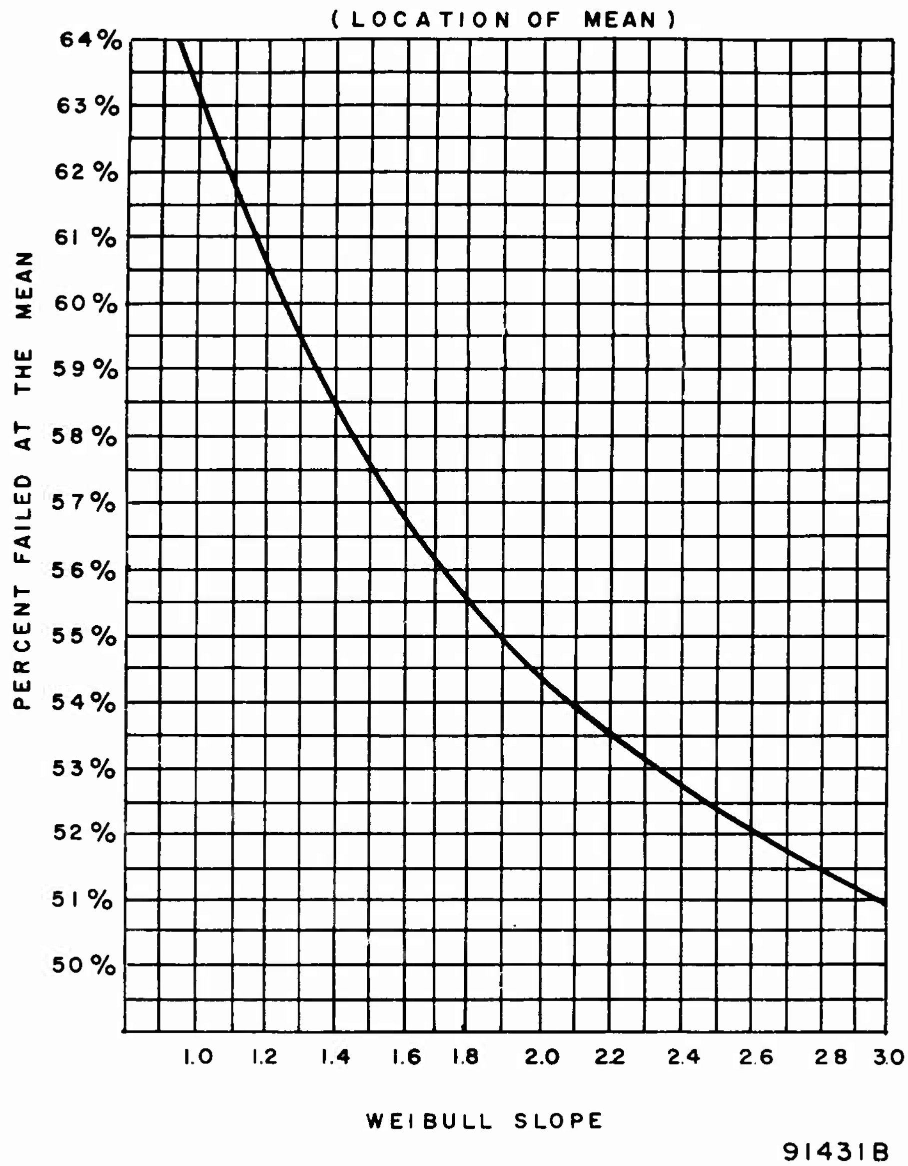

FIGURE 57. PERCENT FAILED AT THE MEAN VERSUS WEIBULL SLOPE (TAKEN FROM REFERENCE 11.18 BY PERMISSION OF THE AUTHOR)

For Figures 31 and 35

$$MLR = \frac{1100}{360} = 3.06$$

Confidence Number

From graphs similar to Figure 58, Confidence Number can be obtained for a given comparison if the Mean Life Ratio, "Total Degrees of Freedom" $[(n_1 - 1)(n_2 - 1)$, where n_1 and n_2 are the sample sizes of the data under comparison], and slopes are known. For Figures 31 and 35:

Slopes: 1.73 and 1.48

MLR = 3.06

Total degrees of freedom = df = (7 - 1)(6 - 1) = 30

In comparing unequal Weibull slopes, a Confidence Number is obtained by considering (a) both slopes equal to the lower slope and (b) both slopes equal to the higher slope. The two Confidence Numbers obtained in this manner are then averaged numerically for a final confidence number. Thus, for Figures 31 and 35:

(1) Use b = 1.73, MLR = 3.06, df = 30. From a plot similar to Figure 58, but for a slope of 1.73, we get:

Confidence No. = 99.7% = $C_{1.73}$

(2) Use b = 1.48, MLR = 3.06, df = 30. Whence, for a plot similar to Figure 58, but for a slope of 1.48, we get:

Confidence No. = 99.7% = $C_{1.48}$

$$\text{Average Confidence No.} = \frac{C_{1.73} + C_{1.48}}{2} = 99.8\%$$

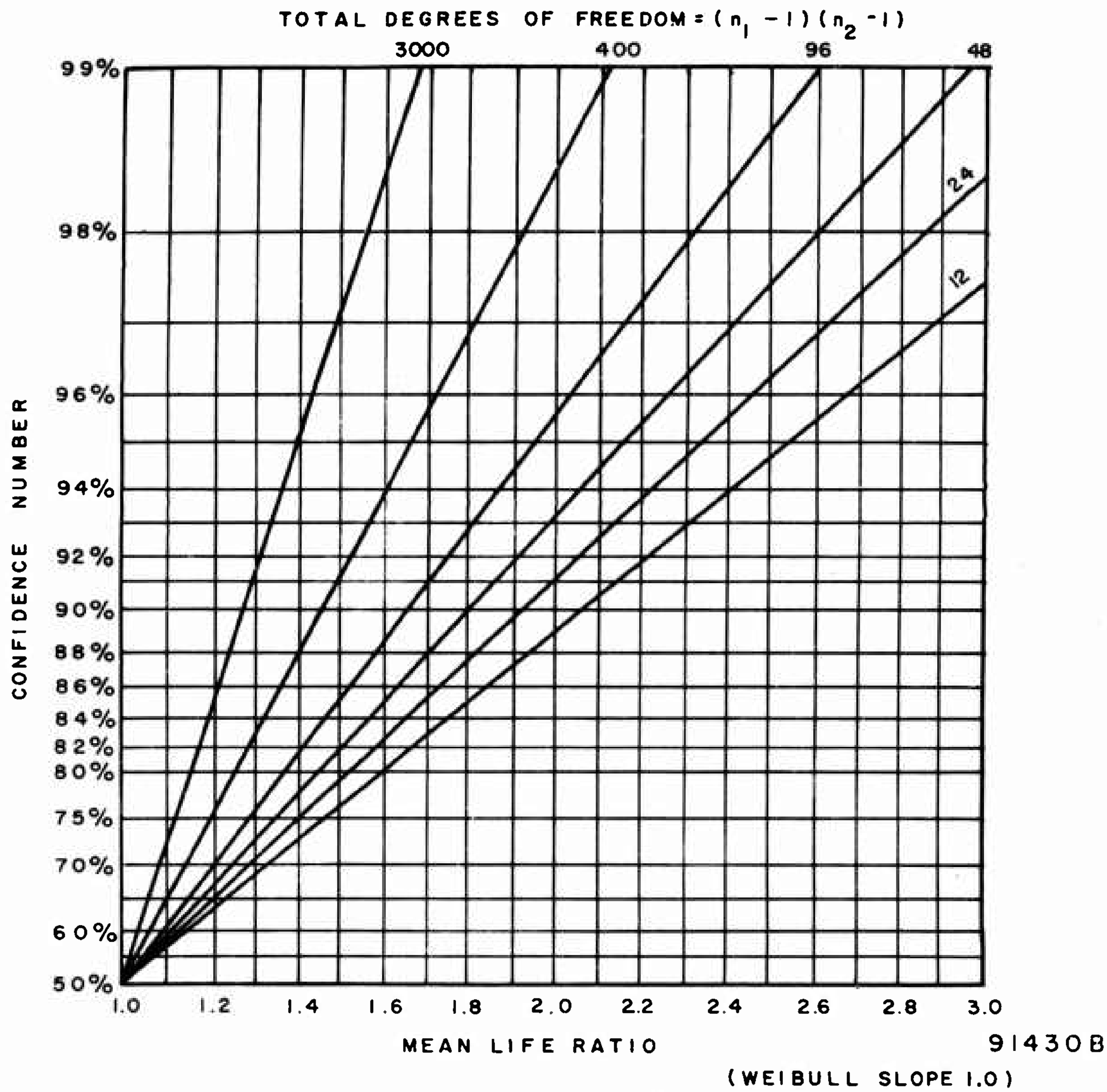

FIGURE 58. CONFIDENCE NUMBER VERSUS MEAN LIFE RATIO (TAKEN FROM REFERENCE 11.18 BY PERMISSION OF THE AUTHOR)

APPENDIX III

SUMMARY OF INDIVIDUAL TESTS FOR 20-MM BEARING MACHINE

TABLE 46. SUMMARY OF TESTS FOR 20-MM BEARING MACHINE

Oil Code C-1003

Test No.	Temp., °F			Atmosphere	Speed, rpm x 10^{-3}	Load, lb	Flow rate, ml/min	Duration, hr	Bearing Deposit Rating		Mode of Failure				Description of Failure	Additional Remarks
	Outer race	Oil in	Sump						Top	Bottom	Oil	Bearing	Rig	Other		
1	700	500	500	N_2	50	100	50	25	5	9						Completed test.
4	700	600	600	N_2	50	100	50	2	1	3		X			Bearing tied up. Races and balls relatively clean but felt rough.	
5	700	600	600	N_2	50	100	50	7	1	3		X			Bearing tied up. Races and balls relatively clean but felt rough. Drain lines part filled with carbon.	
11	700	500	500	N_2	50	100	50	6	1	3			X		"O" ring failure in jet sump.	
12	700	500	500	N_2	50	100	50	25	5	9						Completed test.
16	700	600	600	N_2	50	100	100	10	5	9	X				Bearing tied up. Drain lines plugged.	
17	700	600	600	N_2	50	100	50	15	5	9		X			Bearing tied up. Inner race pitted and cage broken.	Bearing inner race was relieved to reduce "squeeze effect."
18	700	600	500	N_2	50	100	50	7	1	3			X		Bearing tied up. Retainer cap screw had unscrewed.	Oil was drained every 5 hours and replaced.
19	750	600	300	N_2	50	100	50	14	5	9		X			Bearing tied up. Several balls were pitted; one ball frozen in cage.	Oil was drained every 5 hours and replaced.

TABLE 47. OIL DATA FROM 20-MM BEARING RIG

Oil Code C-1003

Test No.	Duration, hr	Viscosity Analysis Temp, °F	Viscosity, cs						Neutralization Number, mg KOH/g						Remarks
			Initial	5 hrs	10 hrs	15 hrs	20 hrs	Final	Initial	5 hrs	10 hrs	15 hrs	20 hrs	Final	
1	25	210	5.65	5.69	5.92	5.99	5.97	6.06	0.05	0.21	0.28	0.31	0.34		
4	2														No viscosity or neut. no. data taken.
5	7														No viscosity or neut. no. data taken.
11	6	210	5.65					9.43							No neut. no. data taken.
12	25	210	5.65					7.72							No neut. no. data taken.
16	10	210	5.65	10.0	7.34			7.60	0.05	1.11	0.39			0.86	
17	15	210	5.65	5.87	7.25	8.56		8.54	0.05	0.20	0.73	0.99		1.24	
18	7	210	5.65	5.50				5.30	0.05	0.56				0.40	Oil was drained every 5 hours and replaced.
19	14	210	5.65	5.54	5.70			5.63	0.05	0.31	0.14			0.08	Oil was drained every 5 hours and replaced.

TABLE 48. SUMMARY OF RUNS FOR 20-MM BEARING RIG

Oil Code Reference "B"

Test No.	Temp, °F			Atmosphere	Speed, rpm x 10^{-3}	Load, lb	Flow rate, ml/min	Duration, hr	Bearing Deposit Rating		Mode of Failure				Description of Failure	Additional Remarks
	Outer race	Oil in	Sump						Top	Bottom	Oil	Bearing	Rig	Other		
2	700	500	500	N_2	50	100	50	4	12	13	X				Bearing tied up. Heavy oil deposits of coke and sludge over inside of rig.	
3	700	500	500	N_2	50	100	50	2	13	14	X				Bearing tied up. Heavy oil coking on the test bearing.	
15	700	500	500	N_2	50	100	50	25	12	13						Completed test.

TABLE 49. OIL DATA FROM 20-MM BEARING RIG

Oil Code Reference "B"

Test No.	Duration, hr	Viscosity Analysis Temp, °F	Viscosity, cs						Neutralization Number, mg KOH/g						Remarks
			Initial	5 hrs	10 hrs	15 hrs	20 hrs	Final	Initial	5 hrs	10 hrs	15 hrs	20 hrs	Final	
2	4														No viscosity or neut. no. data taken.
3	2														No viscosity or neut. no. data taken.
15	25	210	20.3	20.4	27.9	32.2	25.2	26.4	0.34	0.32	0.27	0.29	0.24	0.23	

TABLE 50. SUMMARY OF RUNS FOR 20-MM BEARING RIG

Oil Code GTO-915

Test No.	Temp, °F			Atmosphere	Speed, rpm x 10^{-3}	Load, lb	Flow rate, ml/min	Duration, hr	Bearing Deposit Rating		Mode of Failure				Description of Failure	Additional Remarks
	Outer race	Oil in	Sump						Top	Bottom	Oil	Bearing	Rig	Other		
14	700	500	500	N_2	50	100	50	8	1	3			X		Test oil pump motor burned out.	

TABLE 51. OIL DATA FROM 20-MM BEARING RIG

Oil Code GTO-915

Test No.	Duration, hr	Viscosity Analysis Temp, °F	Viscosity, cs						Neutralization Number, mg KOH/g						Remarks
			Initial	5 hrs	10 hrs	15 hrs	20 hrs	Final	Initial	5 hrs	10 hrs	15 hrs	20 hrs	Final	
14	8	210	3.61	4.22				4.81							No neut. no. data taken.

TABLE 52. SUMMARY OF RUNS FOR 20-MM BEARING RIG

Oil Code LRO-8

Test No.	Temp, °F Outer race	Temp, °F Oil in	Temp, °F Sump	Atmosphere	Speed, rpm x 10^{-3}	Load, lb	Flow rate, ml/min	Duration, hr	Bearing Deposit Rating Top	Bearing Deposit Rating Bottom	Mode of Failure Oil	Mode of Failure Bearing	Mode of Failure Rig	Mode of Failure Other	Description of Failure	Additional Remarks
6	700	600	600	N_2	50	100	50	7	13	14	X				Bearing tied up. Drain lines plugged.	
7	700	600	600	N_2	50	100	50	4	11	12	X				Bearing tied up. Drain lines nearly plugged; heavy coking; bearing cage broken.	
8	700	500	500	N_2	50	100	50	1	3	5			X		Gearbox failure.	
9	700	500	500	N_2	50	100	50	4	13	14		X			Bearing tied up. Bearing cage broken.	
10	700	500	500	N_2	50	100	50	6	13	14		X			Bearing tied up. Races were rough.	
13	700	500	500	N_2	50	100	50	14	13	14	X				Bearing tied up. Drain lines plugged.	

TABLE 53. OIL DATA FROM 20-MM BEARING RIG

Oil Code LRO-8

Test No	Duration, hr	Viscosity Analysis Temp, °F	Viscosity, cs						Neutralization Number, mg KOH/g						Remarks
			Initial	5 hrs	10 hrs	15 hrs	20 hrs	Final	Initial	5 hrs	10 hrs	15 hrs	20 hrs	Final	
6	7	210	6.41	6.59				5.76							No neut. no. data taken.
7	4	210	6.41					6.58							No neut. no. data taken.
8	1														No viscosity or neut. no. data taken.
9	4														No viscosity or neut. no. data taken.
10	6	210	6.41					6.71							No neut. no. data taken.
13	14	210	6.41					6.30							No neut. no. data taken.

TABLE 54. SUMMARY OF RUNS FOR 20-MM BEARING RIG

Oil Code LRO-12

Test No.	Temp, °F			Atmosphere	Speed, rpm x 10^{-3}	Load, lb	Flow rate, ml/min	Duration, hr	Bearing Deposit Rating		Mode of Failure				Description of Failure	Additional Remarks
	Outer race	Oil in	Sump						Top	Bottom	Oil	Bearing	Rig	Other		
20	700	500	500	N_2	50	100	50	25	5	19						Completed test.
21	700	600	600	N_2	50	100	50	4	3	3			X		Bearing tied up, but mode of failure not clear.	Rig inspection at beginning of next run showed test oil pump not functioning.
22	700	700	700	N_2	50	100	50	21	3	19			X		Jet sump heater burned out after 21 hr, but bearing & oil in good condition.	Essentially a completed test.
23	700	600	-	N_2	50	100	50	14	3	13		X			Bearing tied up. Cage was broken; inner race plastically deformed.	Run made without jet sump heater. Main sump temp had to be held near 800° F to give proper oil-in temp.

TABLE 55. OIL DATA FROM 20-MM BEARING RIG

Oil Code LRO-12

Test No.	Duration, hr	Viscosity Analysis Temp, °F	Viscosity, cs						Neutralization Number, mg KOH/g						Remarks
			Initial	5 hrs	10 hrs	15 hrs	20 hrs	Final	Initial	5 hrs	10 hrs	15 hrs	20 hrs	Final	
20	25	100	395.3	365.2	371.8	369.6	365.0	375.5	0	0.20	0.09	0.07	0.06	0.08	
21	4														No viscosity or neut. no. data taken.
22	21	100	395.3	392.8	410.3	441.3	441.7	417.8	0	0.01	0	0	0	0	
23	14														No viscosity or neut. no. data taken.

APPENDIX IV

SUMMARY OF INDIVIDUAL CELANESE OXIDATION TEST RESULTS

TABLE 56. SUMMARY OF CELANESE OXIDATION TEST RESULTS FOR GTO-939

Test Starting Date	Tests	Test Time, Hours: 0	15	20	25	30	35	40	45	50	Total Overhead Acidity mg KOH/g	Total Make-up, g
10-31-60	Viscosity, cs at 100°F	15.06	17.30	18.06	20.38	25.59	30.30	36.94	37.97	39.38	24.66	190.5
	Neut. No., mg KOH/g	0.04	0.50	0.91	2.60	4.36	5.81	7.20	5.26	4.01		
	Make-up, g		18.0	17.0	20.0	23.5	16.5	18.5	18.0	14.5		
10-31-60	Viscosity, cs at 100°F	15.06	17.14	18.25	20.55	24.98	26.64	36.64	40.80	42.86	21.74	179.5
	Neut. No., mg KOH/g	0.04	0.50	0.91	2.54	4.09	5.81	6.48	3.90	5.34		
	Make-up, g		15.5	17.5	19.0	20.0	16.0	19.0	16.5	15.0		
10-31-60	Viscosity, cs at 100°F	15.06	17.27	18.46	20.74	24.75	29.20	30.73	35.92	39.61	20.84	179.0
	Neut. No., mg KOH/g	0.04	0.51	0.99	2.60	3.93	5.33	6.41	5.60	5.34		
	Make-up, g		15.5	16.0	22.0	22.5	15.0	19.0	16.0	12.0		

Oil bath temperature, 425°F; air-flow rate, 96 liters/hr.

TABLE 57. SUMMARY OF CELANESE OXIDATION TEST RESULTS FOR 0-58-24

Test Starting Date	Tests	Test Time, Hours: 0	15	20	25	30	35	40	45	50	Total Overhead Acidity mg KOH/g	Total Make-up, g
11-7-60	Viscosity, cs at 100°F	34.65	55.16	69.23	80.48	97.06	138.62	137.77	156.45	189.91	26.83	168.0
	Neut. No., mg KOH/g	0.14	12.04	8.74	7.18	5.26	5.34	4.90	5.95	5.78		
	Make-up, g		24.0	22.5	19.5	15.5	14.0	13.5	9.5	9.5		
11-7-60	Viscosity, cs at 100°F	34.65	57.52	67.56	74.50	99.92	119.61	139.84	156.16	191.59	26.84	176.5
	Neut. No., mg KOH/g	0.14	12.24	8.85	7.33	5.32	6.02	4.70	5.81	6.42		
	Make-up, g		24.5	23.0	20.5	15.0	13.5	15.5	10.0	9.0		
11-7-60	Viscosity, cs at 100°F	34.65	56.55	61.00	80.84	101.53	122.83	143.67	168.36	202.63	25.64	173.0
	Neut. No., mg KOH/g	0.14	12.11	8.74	6.68	5.17	4.99	4.04	5.53	5.92		
	Make-up, g		25.0	22.5	20.5	14.5	14.0	16.0	10.0	9.5		

Oil bath temperature, 425°F; air-flow rate, 96 liters/hr.

TABLE 58. SUMMARY OF CELANESE OXIDATION TEST RESULTS FOR 0-59-26

Test Starting Date	Tests	Test Time, Hours 0	15	20	25	30	35	40	45	50	Total Overhead Acidity mg KOH/g	Total Make-up, g
12-12-60	Viscosity, cs at 100°F	18.67	20.22	20.50	24.42	28.86	38.91	43.41	60.08	72.01	40.91	83.0
	Neut No., mg KOH/g	0.09	0.18	0.26	1.37	4.04	6.19	6.41	7.25	8.56		
	Make-up, g		5.5	7.0	6.0	10.0	12.5	12.0	8.5	6.0		
12-12-60	Viscosity, cs at 100°F	18.67	20.09	20.54	22.17	27.63	36.40	53.76	54.00	57.40	37.75	93.5
	Neut. No., mg KOH/g	0.09	0.18	0.25	1.21	3.73	5.70	6.88	7.59	7.25		
	Make-up, g		6.5	7.0	7.0	9.0	12.5	13.0	15.5	6.0		
12-12-60	Viscosity, cs at 100°F	18.67	20.24	20.47	22.45	28.00	36.52	44.37	52.00	58.91	42.13	82.5
	Neut. No., mg KOH/g	0.09	0.18	0.27	1.37	3.73	5.61	6.61	7.90	8.44		
	Make-up, g		5.5	5.0	6.5	8.5	11.5	12.0	10.0	6.5		

Oil bath temperature, 425°F, air-flow rate, 96 liters/hr.

TABLE 59. SUMMARY OF CELANESE OXIDATION TEST RESULTS FOR 0-60-11

Test Starting Date	Tests	Test Time, Hours 0	15	20	25	30	35	40	45	50	Total Overhead Acidity mg KOH/g	Total Make-up, g
11-28-60	Viscosity, cs at 100°F	21.24	18.83	18.81[(a)]	-	-	-	-	-	-	-	-
	Neut. No., mg KOH/g	38.54	5.52	5.94	-	-	-	-	-	-		
	Make-up, g		17.5	16.0	-	-	-	-	-	-		
11-28-60	Viscosity, cs at 100°F	21.24	18.83	18.82[(a)]	-	-	-	-	-	-	-	-
	Neut. No., mg KOH/g	38.54	5.95	5.70	-	-	-	-	-	-		
	Make-up, g		15.5	14.0	-	-	-	-	-	-		
11-28-60	Viscosity, cs at 100°F	21.24	18.83	18.59	18.98	18.47	19.56	19.75[(b)]	-	-	11.62	123.0
	Neut. No., mg KOH/g	38.54	5.98	5.88	5.86	5.53	5.26	5.10	-	-		
	Make-up, g		16.0	15.0	15.0	20.5	11.0	11.0	-	-		

Oil bath temperature, 425°F; air-flow rate, 96 liters/hr.
(a) Test terminated after 20 hr due to clogged condenser
(b) Test terminated after 40 hr due to clogged condenser.

TABLE 60. SUMMARY OF CELANESE OXIDATION TEST RESULTS FOR 0-60-12(D-1074)(a)

Test Starting Date	Tests	Test Time, Hours: 0	15	20	25	30	35	40	45	50	Total Overhead Acidity mg KOH/g	Total Make-up, g
10-31-60	Viscosity, cs at 100°F	16.14	17.74	18.08	17.99	18.43	18.65	18.95	18.92	19.20	5.02	102.0
	Neut. No., mg KOH/g	0.13	0.40	0.52	0.62	0.63	0.70	0.75	0.80	0.79		
	Make-up, g		8.0	10.0	13.5	9.5	7.0	11.0	10.5	8.0		
10-31-60	Viscosity, cs at 100°F	16.14	17.61	18.10	18.08	18.23	18.68	18.85	18.99	19.24	4.85	108.0
	Neut. No., mg KOH/g	0.13	0.41	0.52	0.62	0.60	0.71	0.74	0.80	0.75		
	Make-up, g		7.5	12.0	14.5	11.5	5.0	11.5	10.0	10.0		
10-31-60	Viscosity, cs at 100°F	16.14	17.77	17.98	18.15	17.90	18.42	18.94	18.96	19.30	5.04	105.0
	Neut. No., mg KOH/g	0.13	0.43	0.50	0.60	0.60	0.71	0.71	0.72	0.76		
	Make-up, g		8.0	11.0	14.0	10.5	6.5	11.0	10.0	8.0		

Oil bath temperature, 425°F; air-flow rate, 96 liters/hr
(a) Oil received from manufacturer.

TABLE 61. SUMMARY OF CELANESE OXIDATION TEST RESULTS FOR 0-60-12 (D-1087)(a)

Test Starting Date	Tests	Test Time, Hours: 0	15	20	25	30	35	40	45	50	Total Overhead Acidity mg KOH/g	Total Make-up, g
12-5-60	Viscosity, cs at 100°F	16.12	17.57	17.67	17.87	18.07	18.50	21.52	18.77	19.25	3.74	101.5
	Neut. No., mg KOH/g	0.03	0.40	0.37	0.39	0.45	0.54	0.48	0.54	0.53		
	Make-up, g	-	11.0	11.0	10.5	9.5	8.5	11.0	9.0	9.0		
12-5-60	Viscosity, cs at 100°F	16.12	17.66	17.60	17.94	18.20	18.46	21.68	18.82	19.14	3.26	103.0
	Neut. No., mg KOH/g	0.03	0.44	0.37	0.39	0.45	0.47	0.48	0.44	0.50		
	Make-up, g	-	8.0	11.5	11.5	10.5	9.0	10.5	8.5	8.5		
12-5-60	Viscosity, cs at 100°F	16.12	17.48	17.69	18.03	18.06	18.39	20.90	18.87	19.00	4.43	102.5
	Neut. No., mg KOH/g	0.03	0.39	0.39	0.40	0.46	0.40	0.45	0.47	0.55		
	Make-up, g	-	9.5	12.5	9.5	9.5	10.0	10.5	11.0	10.0		

Oil bath temperature, 425°F; air-flow rate, 96 liters/hr.
(a) Oil received from WADD.

TABLE 62. SUMMARY OF CELANESE OXIDATION TEST RESULTS FOR 0-60-13

Test Starting Date	Tests	Test Time, Hours 0	15	20	25	30	35	40	45	50	Total Overhead Acidity mg KOH/g	Total Make-up, g
11-7-60	Viscosity, cs at 100°F	25.67	30.93	31.68	32.34	29.39	33.75	39.07	55.39	61.38	28.87	60.5
	Neut. No., mg KOH/g	0.07	0.78	0.91	1.07	1.49	2.64	4.09	6.50	7.93		
	Make-up, g		5.5	4.5	6.5	3.5	4.5	8.0	5.5	7.5		
11-7-60	Viscosity, cs at 100°F	25.67	29.42	27.74	32.22	38.66	32.32	46.81	53.39	63.34	32.72	61.0
	Neut. No., mg KOH/g	0.07	0.78	0.91	1.07	1.40	2.84	5.42	6.55	7.88		
	Make-up, g		4.5	5.5	7.0	3.0	5.0	10.5	4.5	6.0		
11-7-60	Viscosity, cs at 100°F	25.67	27.12	31.59	38.13	29.56	34.78	42.79	47.79	63.65	33.59	63.5
	Neut. No., mg KOH/g	0.07	0.84	0.90	1.03	1.40	2.49	5.35	6.47	7.87		
	Make-up, g		6.0	5.5	7.5	4.5	4.0	9.5	6.0	7.0		
12-27-60	Viscosity, cs at 100°F	25.67	30.99	31.52	32.46	33.58	36.98	44.20	52.39	60.87	23.92	63.5
	Neut. No., mg KOH/g	0.07	0.67	0.75	0.93	1.12	2.09	3.26	4.47	5.28		
	Make-up, g		5.5	6.0	6.0	6.0	5.0	6.0	6.5	6.5		
12-27-60	Viscosity, cs at 100°F	25.67	30.97	31.60	32.58	33.84	39.18	47.24	56.65	65.82	29.55	68.5
	Neut. No., mg KOH/g	0.07	0.69	0.82	0.93	1.21	2.71	3.82	4.97	5.37		
	Make-up, g		5.0	6.0	6.5	6.0	7.0	7.0	8.0	7.5		
12-27-60	Viscosity, cs at 100°F	25.67	30.76	31.48	32.45	33.24	36.73	43.18	50.74	58.61	24.72	64.0
	Neut. No., mg KOH/g	0.07	0.69	0.78	0.93	0.93	2.04	3.59	4.57	5.14		
	Make-up, g		5.0	6.5	6.0	5.0	6.0	7.0	7.0	6.0		

Oil bath temperature, 425°F; air-flow rate, 96 liters/hr.

TABLE 63. SUMMARY OF CELANESE OXIDATION TEST RESULTS FOR 0-60-23

Test Starting Date	Tests	Test Time, Hours 0	15	20	25	30	35	40	45	50	Total Overhead Acidity, mg KOH/g	Total Make-up, g
10-3-60[a]	Viscosity, cs at 100°F	16.02	17.35	17.64	17.68	17.89	18.17	--	--	--	3.76	73.5
	Neut. No., mg KOH/g	0.05	0.30	0.25	0.33	0.35	0.53	--	--	--		
	Make-up, g		12.0	10.5	11.0	9.0	8.5	--	--	--		
10-3-60[a]	Viscosity, cs at 100°F	16.02	17.59	17.47	17.87	17.72	18.07	--	--	--	3.76	73.0
	Neut. No., mg KOH/g	0.05	0.30	0.29	0.31	0.36	0.53	--	--	--		
	Make-up, g		12.5	11.0	10.5	8.0	10.0	--	--	--		
10-3-60[a]	Viscosity, cs at 100°F	16.02	17.36	17.54	17.72	17.71	17.99	--	--	--	3.64	78.5
	Neut. No., mg KOH/g	0.05	0.30	0.28	0.28	0.35	0.51	--	--	--		
	Make-up, g		14.0	10.5	11.5	10.0	10.0	--	--	--		
10-3-60[a]	Viscosity, cs at 100°F	16.02	17.29	17.49	17.42	17.72	17.97	--	--	--	(b)	76.0
	Neut. No., mg KOH/g	0.05	(b)	(b)	(b)	(b)	0.51	--	--	--		
	Make-up, g		13.0	11.0	12.0	9.5	9.5	--	--	--		
10-3-60[a]	Viscosity, cs at 100°F	16.02	17.29	17.61	17.69	17.80	18.10	--	--	--	(b)	73.0
	Neut. No., mg KOH/g	0.05	(b)	(b)	(b)	(b)	0.49	--	--	--		
	Make-up, g		14.0	10.5	11.5	10.0	10.0	--	--	--		
10-17-60	Viscosity, cs at 100°F	16.02	17.32	17.46	(c)	(c)	17.87	18.05	18.18	18.37	4.37	99.5
	Neut. No., mg KOH/g	0.05	0.37	0.44	(c)	(c)	0.46	(b)	0.48	0.66		
	Make-up, g		12.0	11.5	10.0	10.0	9.0	8.0	11.0	12.5		
10-17-60	Viscosity, cs at 100°F	16.02	17.25	17.48	(c)	(c)	17.99	18.13	18.21	18.31	4.05	96.5
	Neut. No., mg KOH/g	0.05	0.47	0.46	(c)	(c)	0.58	(b)	0.44	0.65		
	Make-up, g		11.0	11.5	10.0	10.0	10.0	8.5	11.0	10.0		
10-17-60	Viscosity, cs at 100°F	16.02	17.28	17.42	(c)	(c)	17.89	18.07	18.12	18.37	4.37	102.5
	Neut. No., mg KOH/g	0.05	0.33	0.47	(c)	(c)	0.57	(b)	0.54	0.66		
	Make-up, g		12.5	12.0	10.5	10.5	9.5	9.0	9.0	12.5		
11-28-60	Viscosity, cs at 100°F	16.02	17.36	17.44	17.63	17.86	18.07	18.18	18.39	18.90	3.32	98.0
	Neut. No., mg KOH/g	0.05	0.29	0.39	0.42	0.45	0.56	0.63	0.70	0.76		
	Make-up, g		10.0	9.0	10.0	10.5	7.0	8.5	9.5	11.0		

Oil bath temperature, 425°F; air flow rate, 96 liters/hr.
(a) Test discontinued after 35 hours in accordance with the first test procedure received from Celanese Chemical Company.
(b) Determinations were not made at time of test.
(c) Samples were inadvertently not taken.

TABLE 64. SUMMARY OF CELANESE OXIDATION TEST RESULTS FOR 0-60-26

Test Starting Date	Tests	Test Time, Hours: 0	15	20	25	30	35	40	45	50	Total Overhead Acidity mg KOH/g	Total Make-up, g
12-12-60	Viscosity, cs at 100°F	15.04	17.44	18.13	21.42	26.44	32.47	37.79	40.86	51.12	17.48	190.0
	Neut. No., mg KOH/g	0.04	0.54	1.04	2.51	4.13	5.12	6.02	5.92	5.21		
	Make-up, g		18.0	19.0	21.0	19.0	21.0	20.5	17.5	13.0		
12-12-60	Viscosity, cs at 100°F	15.04	17.30	18.48	20.79	26.97	33.84	40.04	43.68	45.11	18.89	187.0
	Neut. No., mg KOH/g	0.04	0.54	1.07	2.36	4.51	5.79	6.23	5.64	5.21		
	Make-up, g		16.5	22.5	14.0	22.0	19.5	20.5	19.0	13.0		
12-12-60	Viscosity, cs at 100°F	15.04	17.31	18.50	20.91	24.79	29.90	36.10	40.62	38.10	18.30	186.5
	Neut. No., mg KOH/g	0.04	0.47	1.01	2.36	3.37	4.94	5.55	5.67	5.29		
	Make-up, g		16.0	23.0	17.0	20.0	19.5	20.0	17.5	14.5		

Oil bath temperature, 425°F, air-flow rate, 96 liters/hr.

TABLE 65. SUMMARY OF CELANESE OXIDATION TEST RESULTS FOR 0-60-27

Test Starting Date	Tests	Test Time, Hours: 0	15	20	25	30	35	40	45	50	Total Overhead Acidity mg KOH/g	Total Make-up, g
10-17-60	Viscosity, cs at 100°F	15.00	17.33	18.39	(a)	(a)	31.36	38.61	53.40	49.20	28.20	193.0
	Neut. No. mg KOH/g	0.06	0.50	1.18	(a)	(a)	7.79	(b)	10.08	7.94		
	Make-up, g		20.5	18.0	19.5	19.5	21.0	20.0	20.0	19.0		
10-17-60	Viscosity, cs at 100°F	15.00	17.35	18.09	(a)	(a)	29.75	34.43	39.74	45.97	28.65	188.0
	Neut. No., mg KOH/g	0.06	0.47	1.18	(a)	(a)	7.79	(b)	9.98	9.22		
	Make-up, g		19.0	19.0	18.0	19.0	20.0	20.0	20.0	19.0		
10-17-60	Viscosity, cs at 100°F	15.00	17.19	18.13	(a)	(a)	28.64	30.43	34.67	46.80	27.68	179.5
	Neut. No., mg KOH/g	0.06	0.50	1.18	(a)	(a)	7.79	(b)	9.86	8.48		
	Make-up, g		19.0	19.0	18.5	18.0	18.5	19.0	18.5	18.5		
12-5-60	Viscosity, cs at 100°F	15.00	17.60	18.86	21.59	26.69	33.73	45.91	43.45	47.62	20.73	196.0
	Neut. No. mg KOH/g	.07	0.55	1.01	2.33	4.08	6.28	6.03	6.44	5.52		
	Make-up, g		18.5	20.0	22.5	21.5	19.5	19.5	15.5	13.5		
12-27-60	Viscosity, cs at 100°F	15.00	17.59	19.28	22.65	27.85	33.27	38.41	42.51	45.31	18.60	189.0
	Neut. No., mg KOH/g	0.07	0.56	1.34	2.86	3.69	4.66	4.93	4.97	4.50		
	Make-up, g		17.5	19.5	21.5	22.0	21.0	18.5	17.0	14.5		
12-27-60	Viscosity, cs at 100°F	15.00	17.50	18.96	22.50	28.25	35.99	42.32	48.49	51.93	22.04	188.0
	Neut. No., mg KOH/g	0.07	0.53	1.37	2.85	4.01	4.96	5.41	5.39	4.98		
	Make-up, g		15.5	18.0	21.0	21.5	21.0	17.0	17.5	16.5		
12-27-60	Viscosity, cs at 100°F	15.00	17.37	18.80	21.74	26.44	32.57	37.47	41.90	45.21	19.53	183.5
	Neut. No., mg KOH/g	0.07	0.53	0.99	2.79	4.03	4.34	5.03	4.79	4.48		
	Make-up, g		16.0	18.5	21.0	21.0	21.0	17.5	17.0	16.0		

Oil bath temperature 425°F; air-flow rate, 96 liters/hr

(a) Samples were inadvertently not taken.

(b) Determinations were not made at time of test.

TABLE 66. SUMMARY OF CELANESE OXIDATION TEST RESULTS FOR 0-60-12 OBTAINED BY CELANESE CHEMICAL COMPANY

Tests	Test Time, Hours 0	15	20	25	30	35	40	45	50	Total Overhead Acidity mg KOH/g	Total Make-up, g
Viscosity, cs at 100°F	15.98	--	--	17.66	17.90	18.10	18.24	18.39	--	4.6	--
Neut. No., mg KOH/g	<0.05	--	--	0.33	0.38	0.40	0.40	0.44	--		
Make-up, g		--	--	11.0	11.0	12.0	10.0	10.0	--		
Viscosity, cs at 100°F	15.98	--	--	17.70	17.90	18.09	18.29	18.43	--	4.6	--
Neut. No., mg KOH/g	<0.05	--	--	0.32	0.36	0.41	0.43	0.46	--		
Make-up, g		--	--	11.0	12.0	11.0	9.0	9.0	--		
Viscosity, cs at 100°F	15.86	--	18.11	18.41	18.53	18.78	19.06	19.27	--	5.7	--
Neut. No., mg KOH/g	0.03	--	0.48	0.52	0.77	0.61	0.62	0.77	--		
Make-up, g		--	12.0	10.0	10.0	8.0	10.0	7.0	--		
Viscosity, cs at 100°F	15.86	--	17.91	18.22	18.55	18.79	18.98	19.16	--	5.7	--
Neut. No., mg KOH/g	0.03	--	0.47	0.51	0.70	0.60	0.71	0.78	--		
Make-up, g		--	12.0	11.0	11.0	9.0	10.0	7.0			

TABLE 67. SUMMARY OF CELANESE OXIDATION TEST RESULTS FOR 0-60-23 OBTAINED BY CELANESE CHEMICAL COMPANY

Tests	Test Time, Hours 0	15	20	25	30	35	40	45	50	Total Overhead Acidity mg KOH/g	Total Make-up, g
Viscosity, cs at 100°F	16.11	--	17.26	18.32	18.70	20.66	26.43	31.72	--	27.5	--
Neut. No., mg KOH/g	0.06	--	0.41	0.43	0.73	1.97	4.23	5.58	--		
Make-up, g		--	10.0	9.0	10.0	10.0	17.0	12.0	--		
Viscosity, cs at 100°F	16.11	--	17.11	18.19	18.57	20.17	24.56	30.54	--	26.1	--
Neut. No., mg KOH/g	0.06	--	0.42	0.44	0.71	1.68	3.77	6.28	--		
Make-up, g		--	11.0	9.0	11.0	11.0	15.0	16.0	--		

APPENDIX V

SUMMARY OF INDIVIDUAL IMPACT TEST RESULTS

TABLE 68. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-5 WITH LOX

Threshold Value Determined: <9 in. (<15 ft-lb)

Tests Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	42	4	1	Low explosion	Char
2	21	1	1	Low explosion	Oil burned
3	15	5	1	Low explosion	Char
4	9	3	1	High explosion	
	48	2			Blank tests

SwRI specimen cups used. 0.59 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 69. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-9 WITH LOX

Threshold Value Determined: 9 in. (15 ft-lb)

Test Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	42	8	1	Med. explosion	Rebound
2	21	20	1	High explosion	
	48	2			Blank tests
3	15	5	1	High explosion	Extreme Char
4	9	20	0		
5	12	8	1	High explosion	Extreme Char
	48	2			Blank tests

SwRI specimen cups used. 0.59 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 70. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-18 WITH LOX

Threshold Value Determined: 12 in. (20 ft-lb)

Test Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	42	6	1	High explosion	
2	21	3	1	High explosion	
3	15	4	1	High explosion	
	48	2			Blank tests
4	12	20	0		
	48	2			Blank tests
5	9	20	0		
	48	2			Blank tests

SwRI specimen cups used. 0.63 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 71. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-26 WITH LOX

Threshold Value Determined: >45 in. (>75 ft-lb)

Tests Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	42	20	0		
	48	4			Blank tests
2	45	20	0		
	48	2			Blank tests

SwRI specimen cups used. 0.55 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 72. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-32 WITH LOX

Threshold Value Determined: <21 in. (<35 ft-lb)

Test Series	Drop Hgt, in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	21	7	1	High explosion	Rebound
	48	4			Blank tests
2	21	2	1	Medium explosion	
	48	2			Blank tests

SwRI specimen cups used. 0.64 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 73. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-34 WITH LOX

Threshold Value Determined: 9 in. (15 ft-lb)

Test Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	42	6	1	Low explosion	Char
2	21	3	1	Low explosion	Char
3	15	4	1	Med. explosion	Oil burned
4	9	20	0		
	48	4			Blank tests
5	12	14	1	Low explosion	
	48	2			Blank tests

SwRI specimen cups used. 0.57 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 74. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-35 WITH LOX

Threshold Value Determined: 21 in. (35 ft-lb)

Test Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	42	5	1	Low explosion	
2	21	20	0		
	48	4			Blank tests
3	36	20	0		
4	39	14	1(a)	High explosion	
5	39	3	1	Low explosion	Rebound
	48	4			Blank tests
6	33	4	1(a)	High explosion	
7	33	19	1	Low explosion	
	48	4			Blank tests
8	30	20	0		
9	36	9	1	Low explosion	
10	27	7	1	High explosion	
	48	4			Blank tests
11	24	3	1	Low explosion	
12	30	3	1	High explosion	
13	18	20	0		
	48	2			Blank tests

SwRI specimen cups used. 0.57 ml of test sample used to obtain 0.050 in. test sample thickness.

(a) This reaction may have been due to excessive cracking of the sample during cooling, therefore another series of tests were run to confirm this reaction.

TABLE 75. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-58 WITH LOX

Threshold Value Determined: <21 in. (<35 ft-lb)

Test Series	Drop Hgt, in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	21	19	1	High explosion	
	48	4			Blank tests
2	21	17	1	Medium explosion	Rebound
	48	2			Blank tests

SwRI specimen cups used. 0.60 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 76. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-59 WITH LOX

Threshold Value Determined: <21 in. (<35 ft-lb)

Test Series	Drop Hgt, in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	21	2		High explosion	
	48	2			Blank tests

SwRI specimen cups used. 0.62 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 77. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-60 WITH LOX

Threshold Value Determined: <21 in. (<35 ft-lb)

Test Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	1			Blank test
1	21	20	3	1 High explosion	
				1 Medium explosion	Rebound
				1 Low explosion	Rebound
	48	1			Blank test

SwRI specimen cups used. 0.64 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 78. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-61 WITH LOX

Threshold Value Determined: <9 in. (<15 ft-lb)

Test Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	21	9	1	High explosion	
2	15	3	1	High explosion	
3	12	6	1	Low explosion	
	48	2			Blank tests
4	9	8	1	High explosion	
	48	2			Blank tests

SwRI specimen cups used. 0.65 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 79. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-62 WITH LOX

Threshold Value Determined: 12 in. (20 ft-lb)

Test Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	21	10	0		
2	42	2	1	High explosion	
3	36	3	1	High explosion	
4	30	2	1	High explosion	
5	24	3	1	High explosion	
6	18	7	1	High explosion	
7	21	1	1	Med. explosion	Rebound
8	12	20	0		
	48	2			Blank tests
9	15	3	1	High explosion	
10	9	20	0		
	48	2			Blank tests

SwRI specimen cups used. 0.58 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 80. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE CG-63 WITH LOX

Threshold Value Determined: <21 in. (<35 ft-lb)

Test Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	21	3	1	High explosion	
	48	2			Blank tests

SwRI specimen cups used. 0.64 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 81. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE D-1060 WITH LOX

Threshold Value Determined: <21 in. (<35 ft-lb)

Test Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	1			Blank test
1	21	20	2	1 High explosion 1 Medium explosion	Rebound
	48	1			Blank test

SwRI specimen cups used. 0.58 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 82. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE D-1066 WITH LOX

Threshold Value Determined: 33 in. (55 ft-lb)
(1st Series)

Test Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	21	20	0		
	48	3			Blank tests
2	42	20	1	Low explosion	Rebound
	48	3			Blank tests
3	36	20	2	Low explosion	Rebounds
	48	2			Blank tests
4	30	20	0		
	48	2			Blank tests
5	33	20	0		

Threshold Value Determined: >42 in. (>70 ft-lb)
(2nd Series)

Test Series	Drop Hgt., in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	42	20	0		
	48	2			Blank tests
2	36	20	0		

SwRI specimen cups used. 0.56 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 83. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE D-1071 WITH LOX

Threshold Value Determined: >45 in. (>75 ft-lb)

Test Series	Drop Hgt, in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	2			Blank tests
1	42	20	0		
	48	2			Blank tests
2	45	20	0		

SwRI specimen cups used. 0.50 ml of test sample used to obtain 0.050 in. test sample thickness.

TABLE 84. SUMMARY OF IMPACT TEST RESULTS ON SAMPLE D-1093 WITH LOX

Threshold Value Determined: 27 in. (45 ft-lb)
(1st Series)

Test Series	Drop Hgt. in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	5			Blank tests
1	48	2	1	High explosion	
2	42	8	1	Low explosion	
	36	5			Blank tests
3	36	11	1	High explosion	
	30	5			Blank tests
4	30	9	1	Low explosion	
5	24	20	0		
	27	5			Blank tests
6	27	20	0		

ABMA specimen cups used. 0.50 ml of test sample was used in each cup.

Threshold Value Determined: 33 in. (55 ft-lb)
(2nd Series)

Test Series	Drop Hgt. in.	No. of Tests	No. of Reactions	Nature of Reactions	Remarks
	48	1			Blank tests
1	42	6	1	Low explosion	Rebound
2	36	8	1	Medium	
	48	1			Blank tests
3	30	20	0		
	48	3			Blank tests
4	33	20	0		

SwRI specimen cups used. 0.50 ml of test sample was used in each cup.

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Contract No. AF 33(616)-7223, Project No. 3044. Unclassified Report.

The work performed under this program was concerned with lubrication problems associated with advanced primary and secondary propulsion systems for aviation and space applications. The program was divided into four principal phases of investigation: gear lubrication, bearing lubrication, lubricant oxidation, and impact sensitivity of materials in contact with strong oxidizers. The effort has been devoted largely to gear and bearing lubrication. In the gear lubrication and the bearing lubrication phases, the emphasis has been primarily on the development of suitable test methods for determining the capabilities of liquid lubricants intended for use in high-temperature applications. Lubricant oxidation determinations have been made on organic liquid lubricants using the equipment and test procedure recommended by the Celanese Chemical Company. The impact sensitivity work has been concerned with the impact sensitivity of liquid lubricants, greases and sealants in contact with liquid oxygen and with test method development in an endeavor to improve the repeatability and reproducibility of the impact test using the ABMA impact tester.

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LUBRICATION RESEARCH AND TEST METHOD DEVELOPMENT FOR AEROSPACE PROPULSION SYSTEMS
B. B. Baber, P. M. Ku, C. W. Lawler, L. W. Lew, H. E. Staph

May 1961, 225 pp with appendixes, ASD TR 61-85
Contract No. AF 33(616)-7223, Project No. 3044. Unclassified Report.

The work performed under this program was concerned with lubrication problems associated with advanced primary and secondary propulsion systems for aviation and space applications. The program was divided into four principal phases of investigation: gear lubrication, bearing lubrication, lubricant oxidation, and impact sensitivity of materials in contact with strong oxidizers. The effort has been devoted largely to gear and bearing lubrication. In the gear lubrication and the bearing lubrication phases, the emphasis has been primarily on the development of suitable test methods for determining the capabilities of liquid lubricants intended for use in high-temperature applications. Lubricant oxidation determinations have been made on organic liquid lubricants using the equipment and test procedure recommended by the Celanese Chemical Company. The impact sensitivity work has been concerned with the impact sensitivity of liquid lubricants, greases and sealants in contact with liquid oxygen and with test method development in an endeavor to improve the repeatability and reproducibility of the impact test using the ABMA impact tester.

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1. Introduction
2. Gear Lubrication
3. Bearing Lubrication
4. Lubricant Oxidation
5. Impact Sensitivity

I. Contract No. AF 33(616)-7223, Project No. 3044
II. B. B. Baber, P. M. Ku, C. W. Lawler, L. W. Lew, H. E. Staph
III. Lubrication Research and Test Method Development for Aerospace Propulsion Systems

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